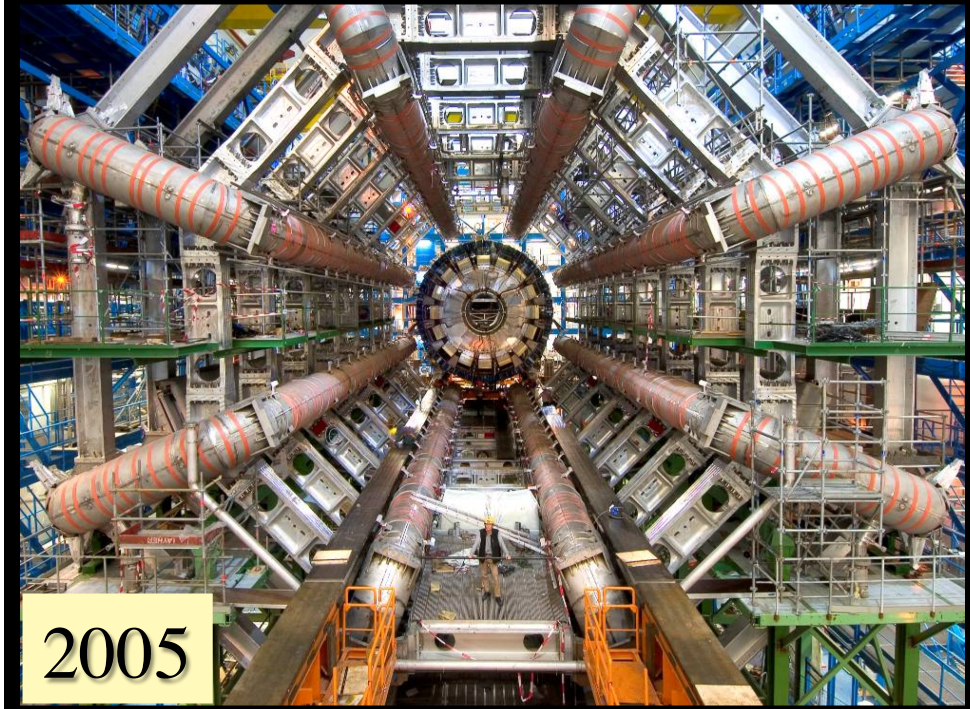
LHC: the first three years …
and the next two decades

Beate Heinemann

University of California, Berkeley and Lawrence Berkeley National Laboratory



New York University, April 2013

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and the next two decades

Beate Heinemann

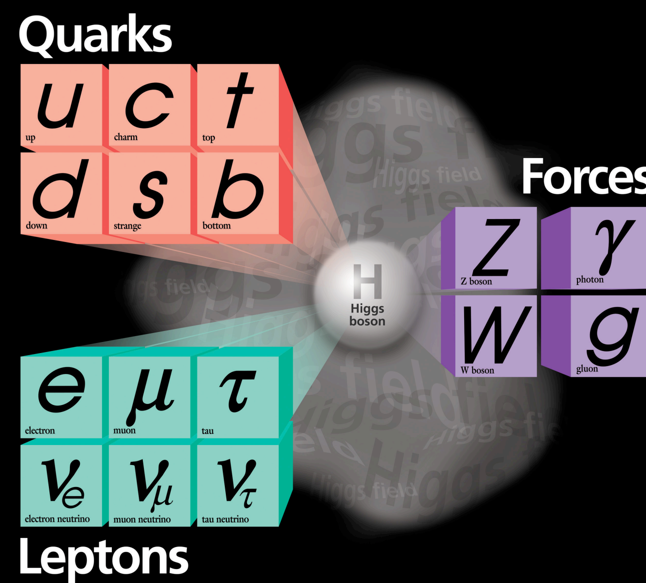
University of California, Berkeley and Lawrence Berkeley National Laboratory

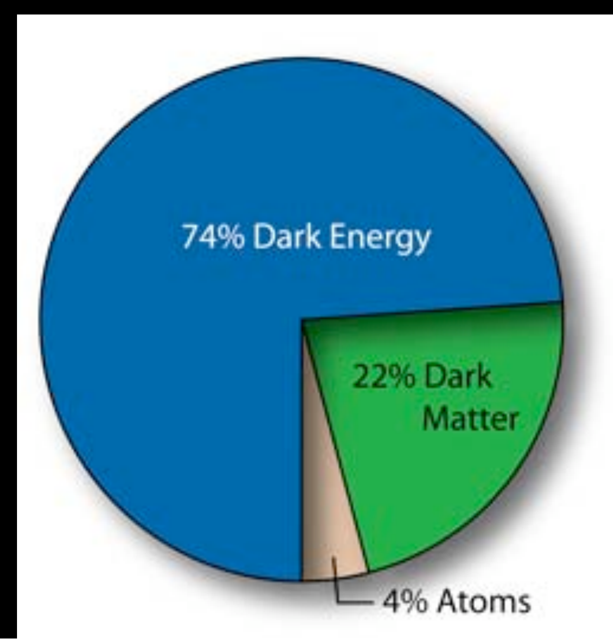
- Introduction
- Run-1 (2009-2013)
- Future Plans
- Conclusions

New York University, April 2013

What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
  - **Why do particles have mass?**
    - Possible answer: The Higgs boson
  - **Why is gravity so weak?**
    - Possible answers: supersymmetric particles, extra spatial dimensions
  - **What is Dark Matter?**
    - Possible answer: the lightest supersymmetric particle
  - **The unexpected …**

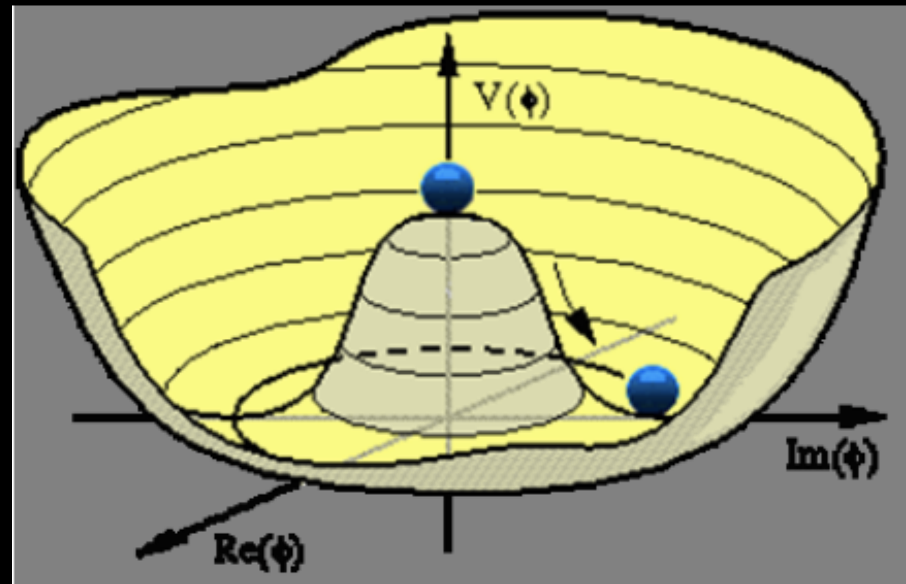




The Higgs Mechanism

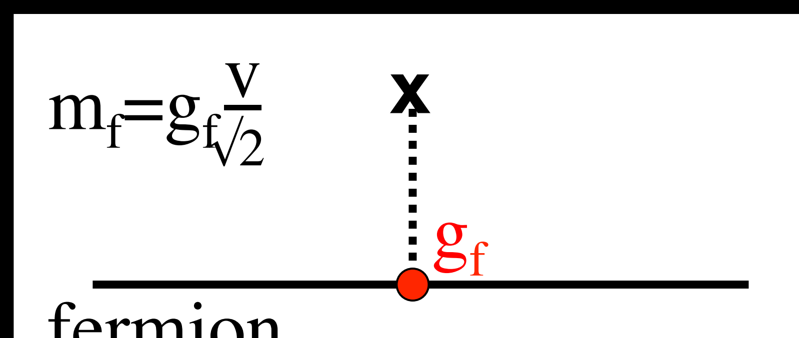
- 1964
  - P. Higgs
  - R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:

$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

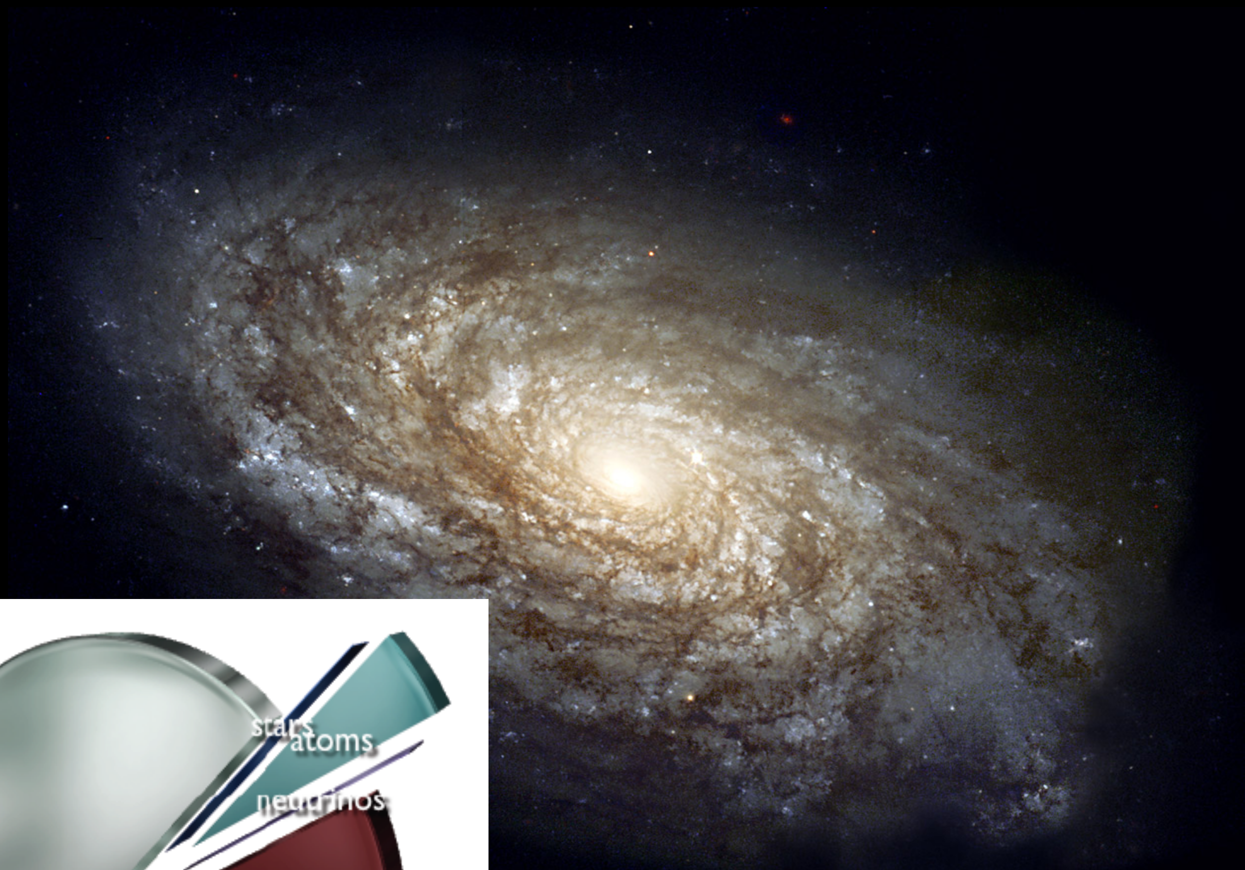


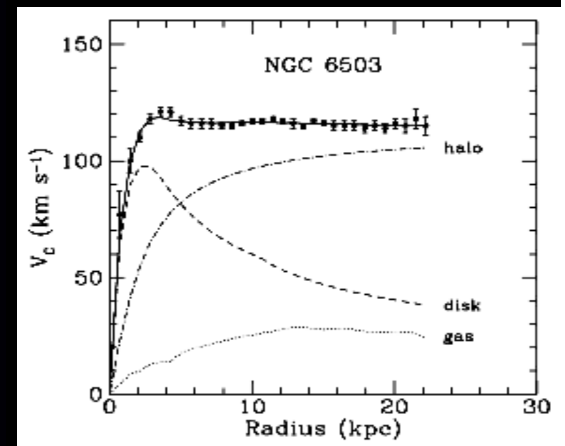
$\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV.

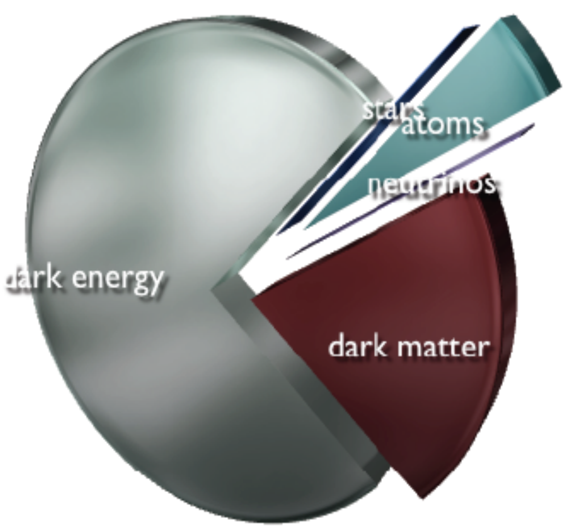
- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^{\pm}_L, Z_L$
  - 1 neutral Higgs boson
- Masses of fermions m_f proportional to unknown Yukawa couplings g_f



What is the Dark Matter?





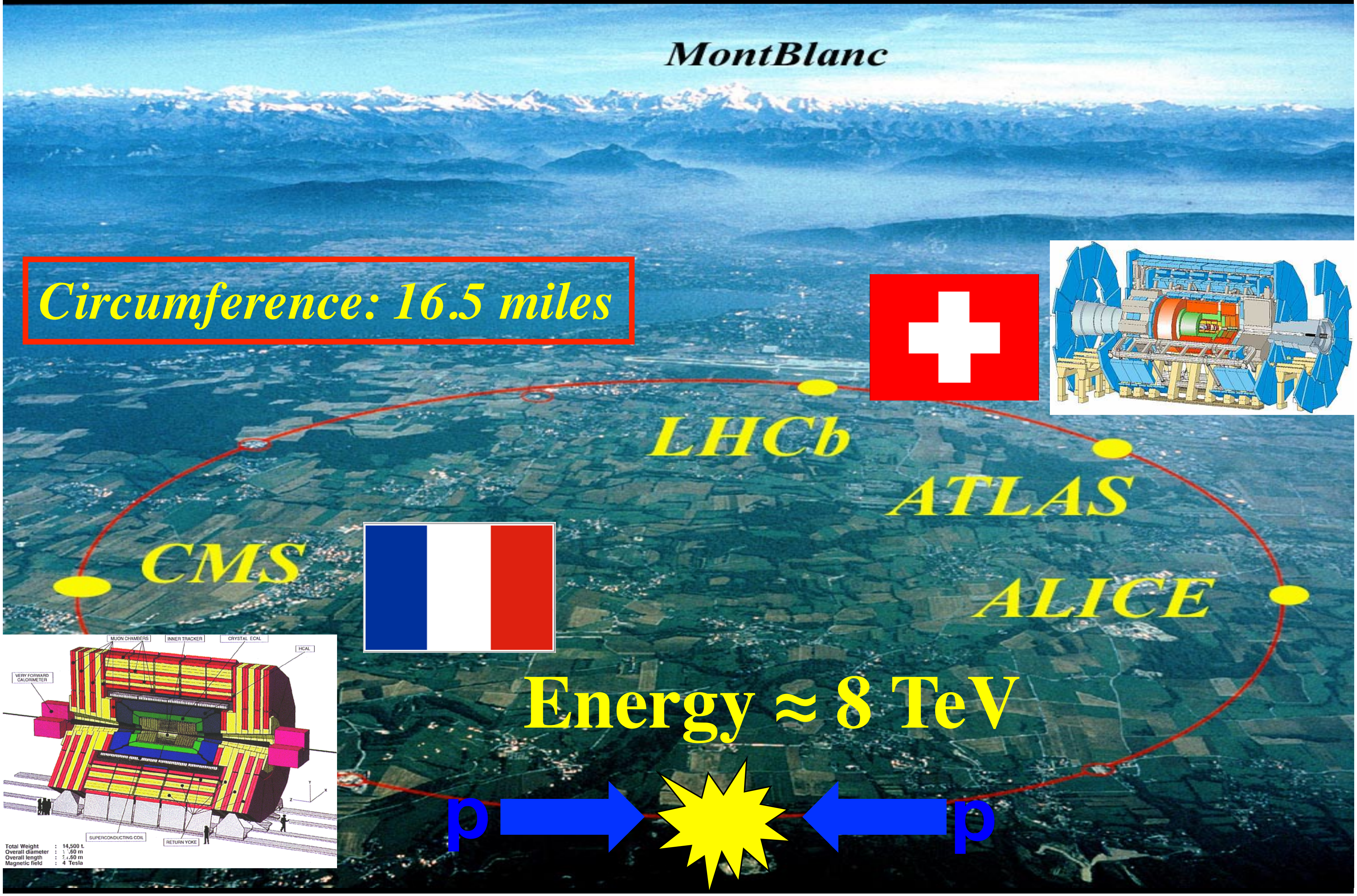


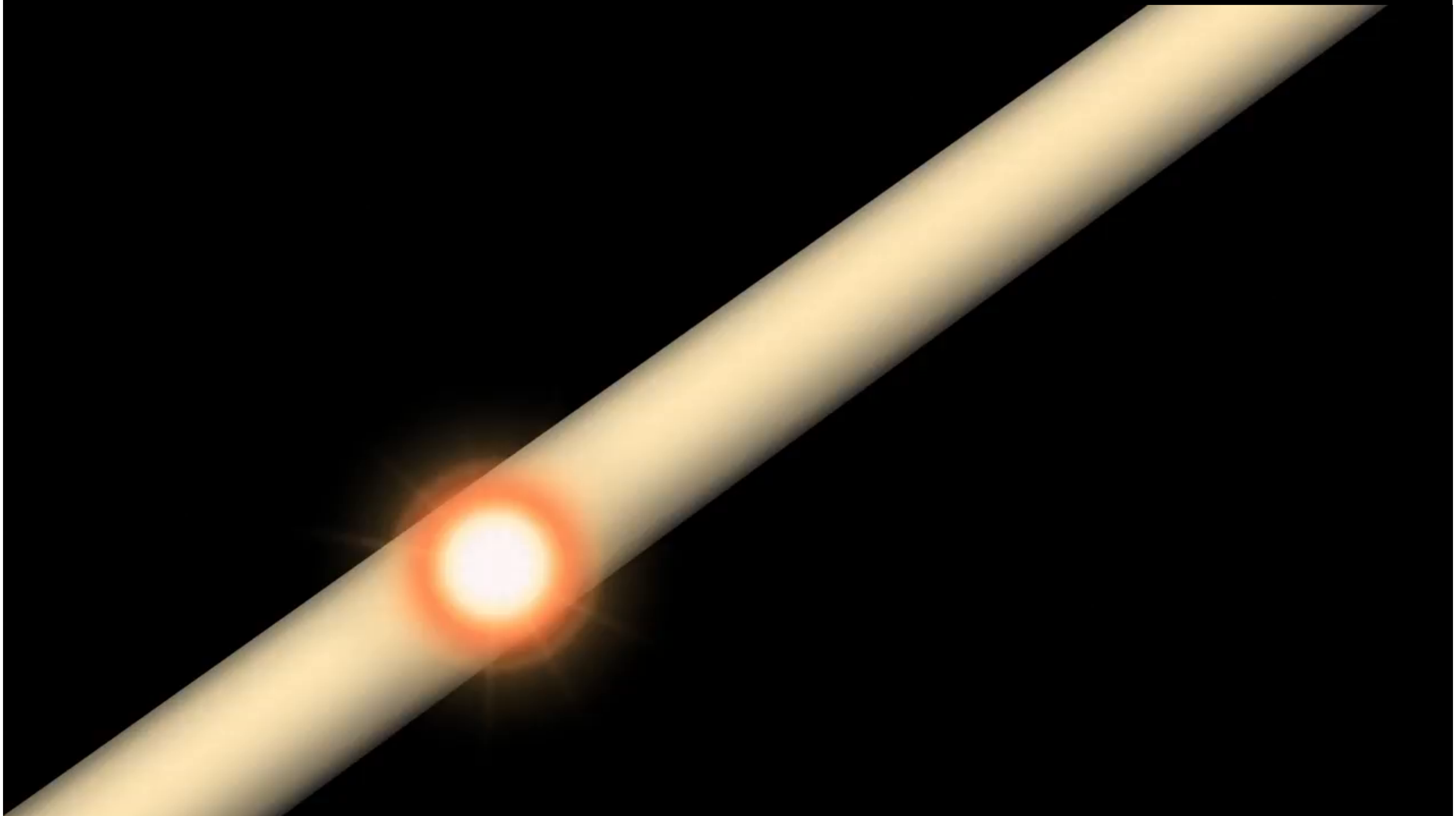
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

Standard Model only accounts for ~20% of the matter of the Universe:

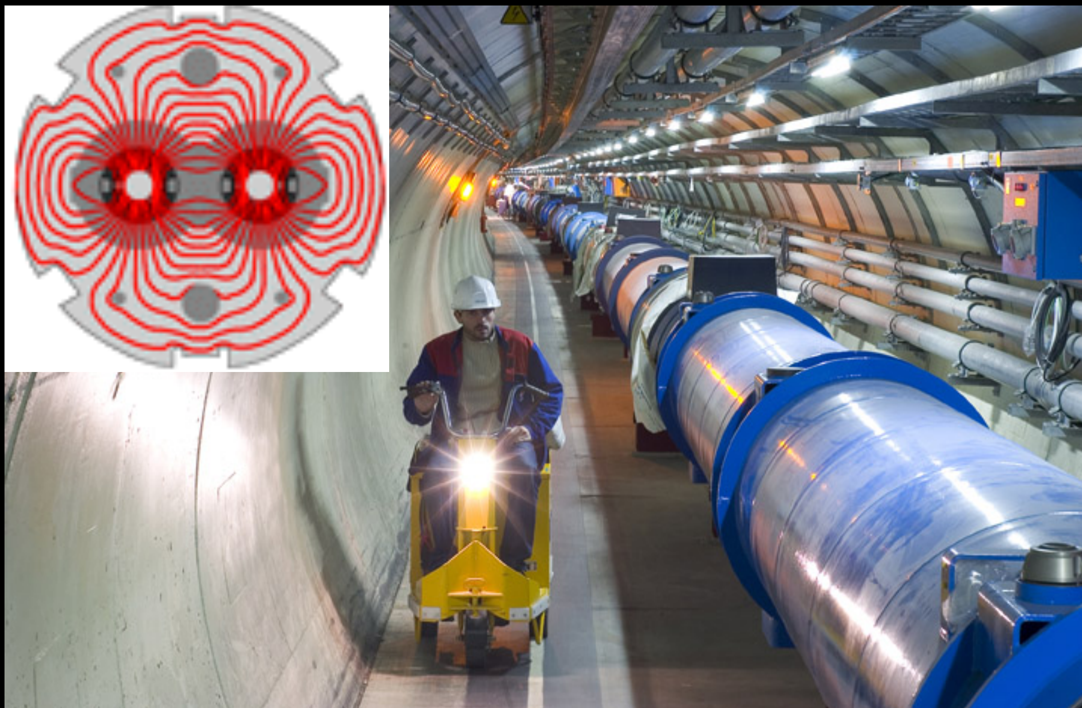
Many theories predict production of dark matter particles at the LHC

The Large Hadron Collider (LHC)



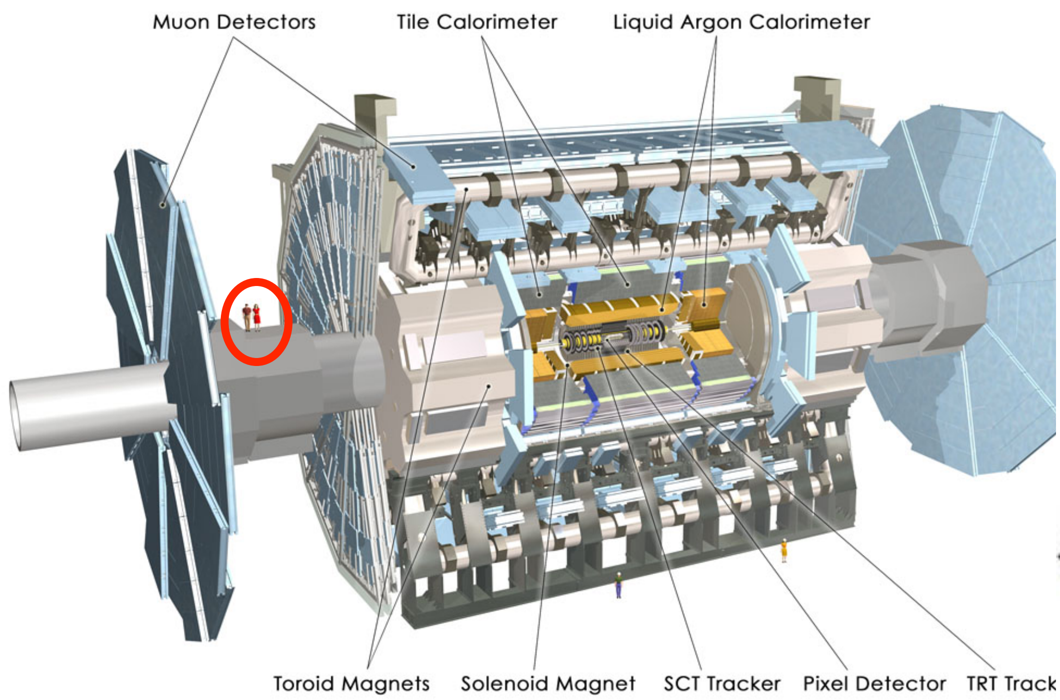


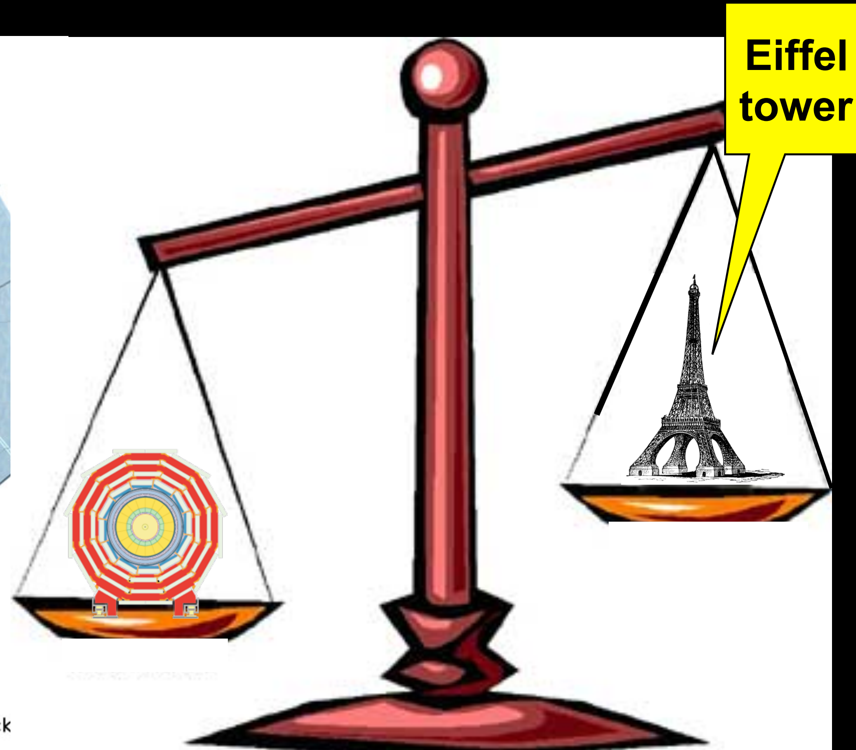
LHC Accelerator



- 30,000 tons of 8.4T dipole magnets
- Cooled to 1.9K with 90 tons of liquid helium
- Energy of beam = 362 MJ
  - Kinetic energy of 15 ton truck at 500 mph

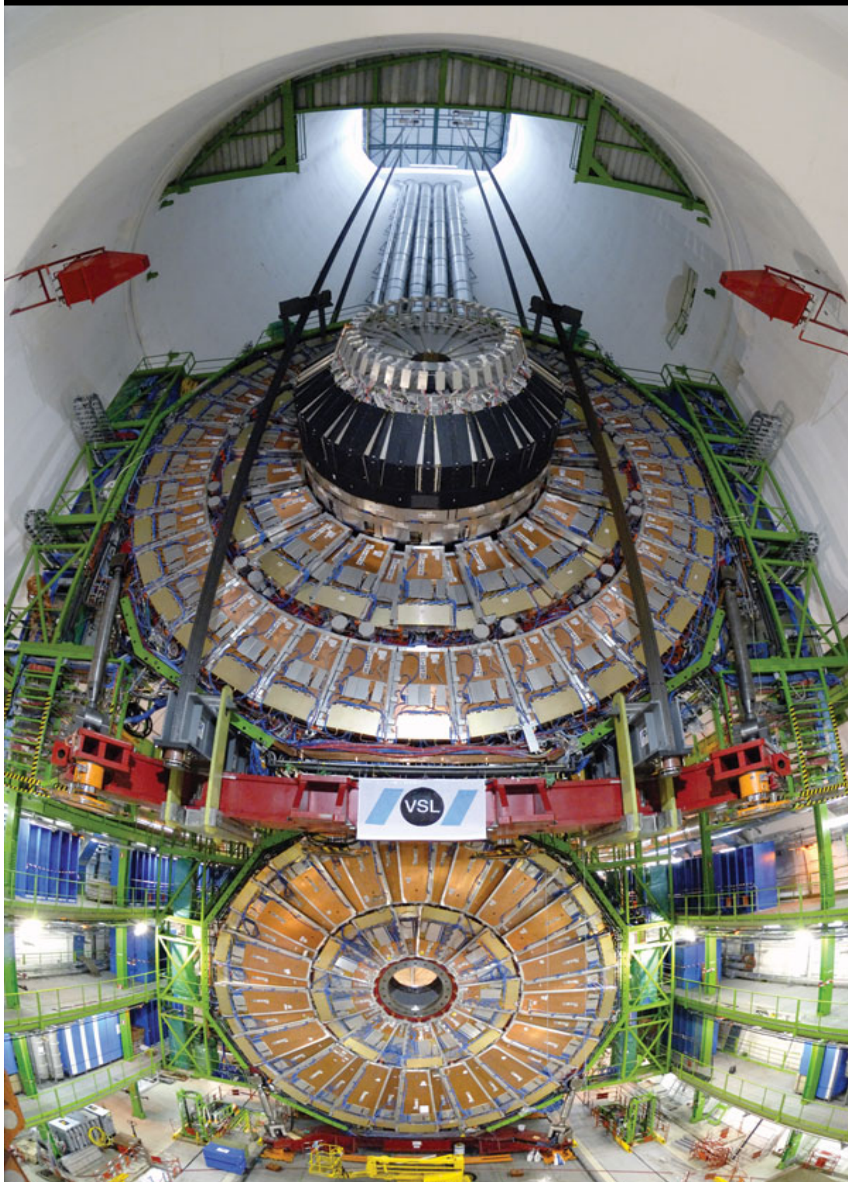
ATLAS and CMS Detectors

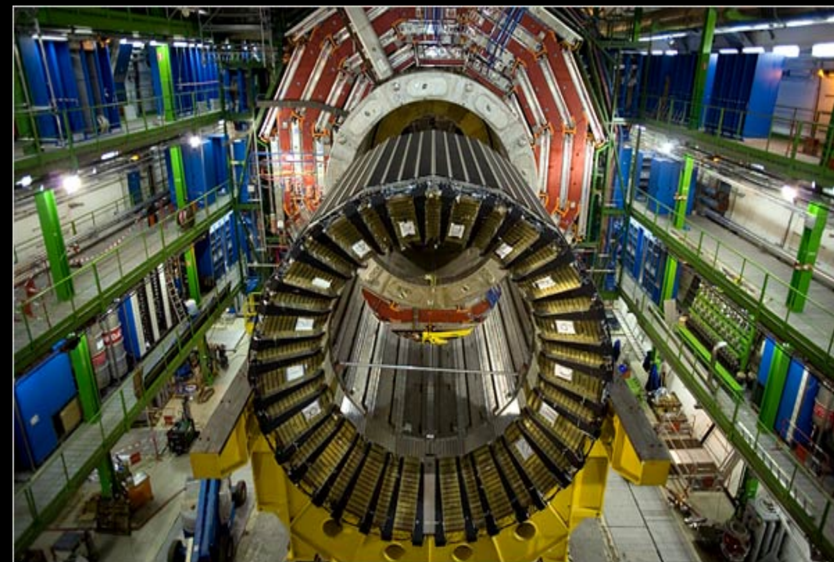


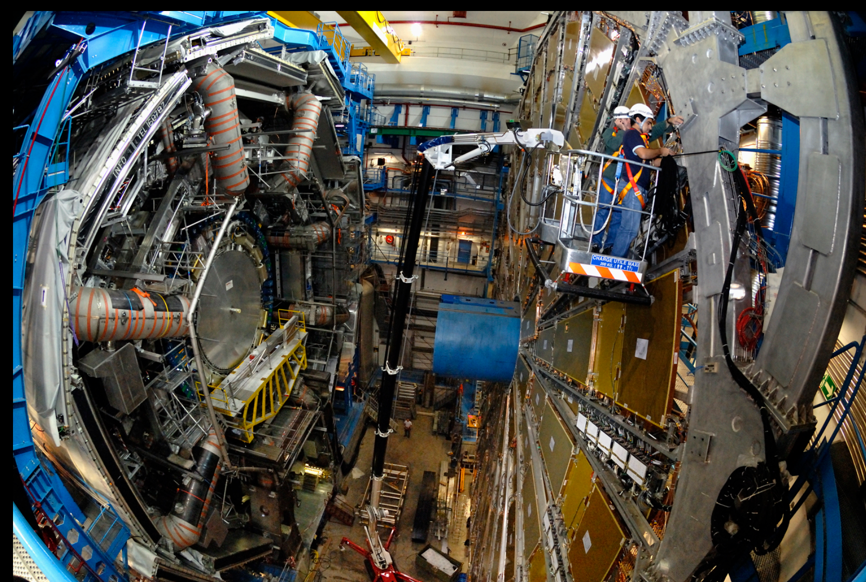


	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

ATLAS and CMS Detector Assembly

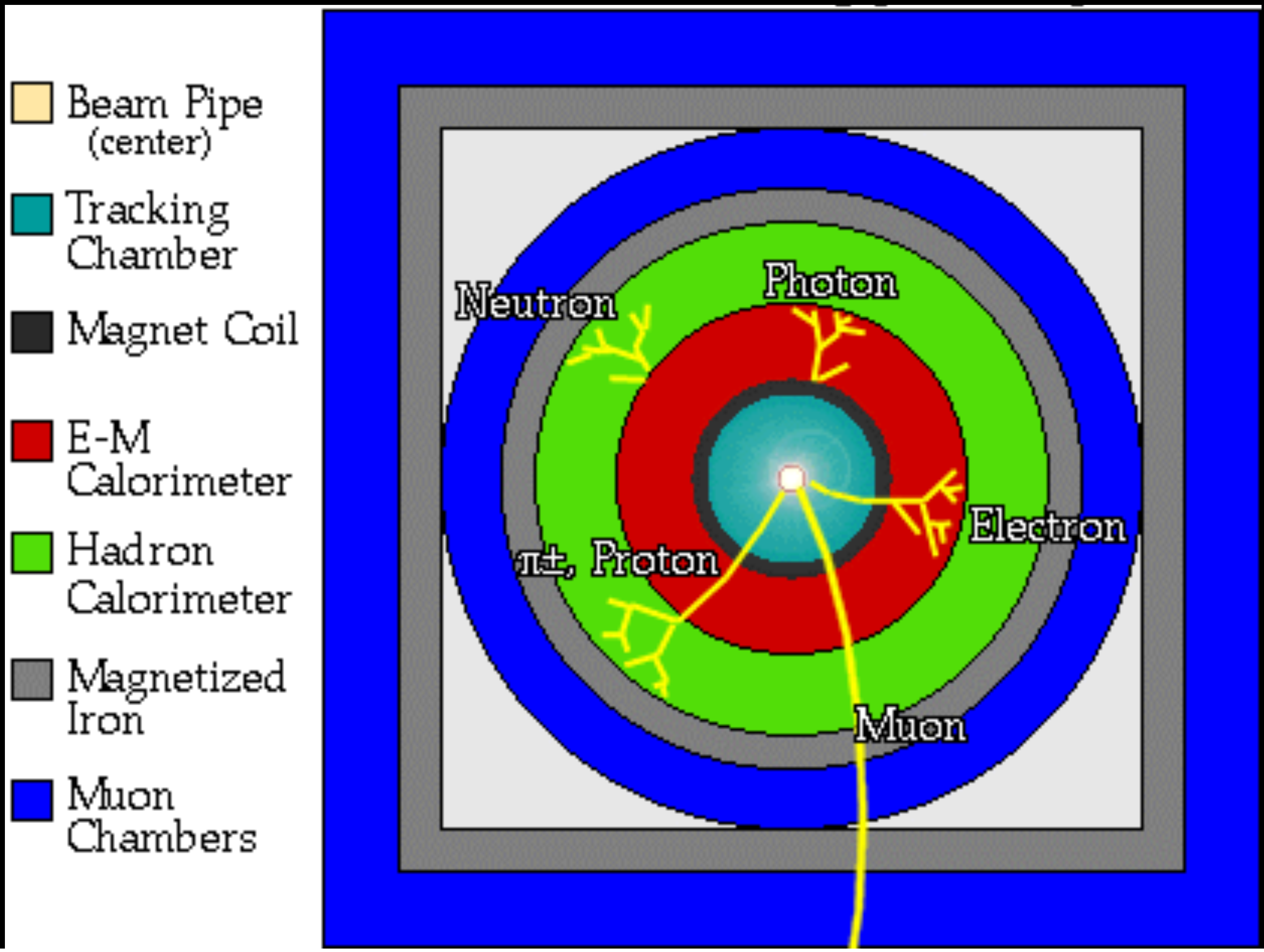




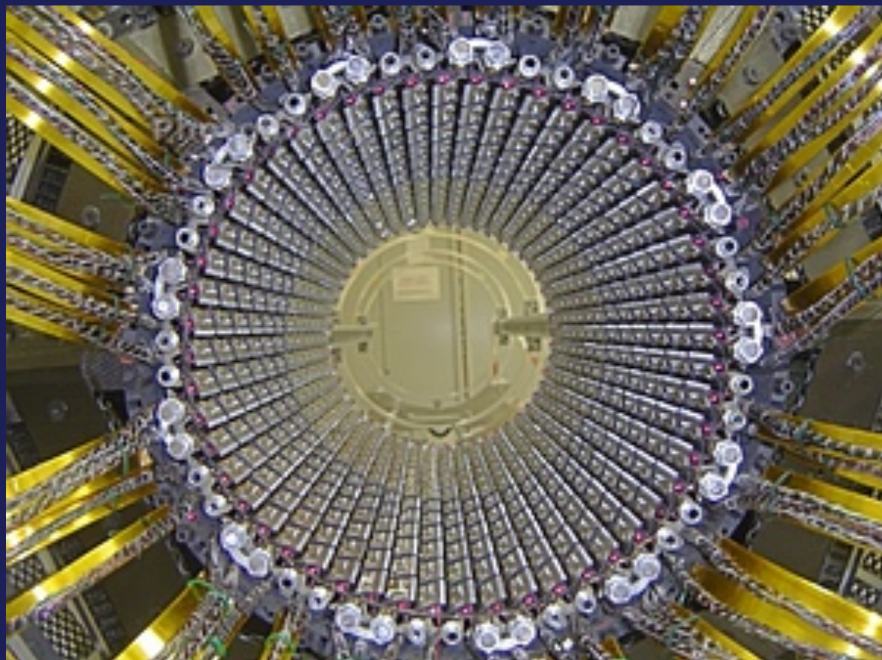


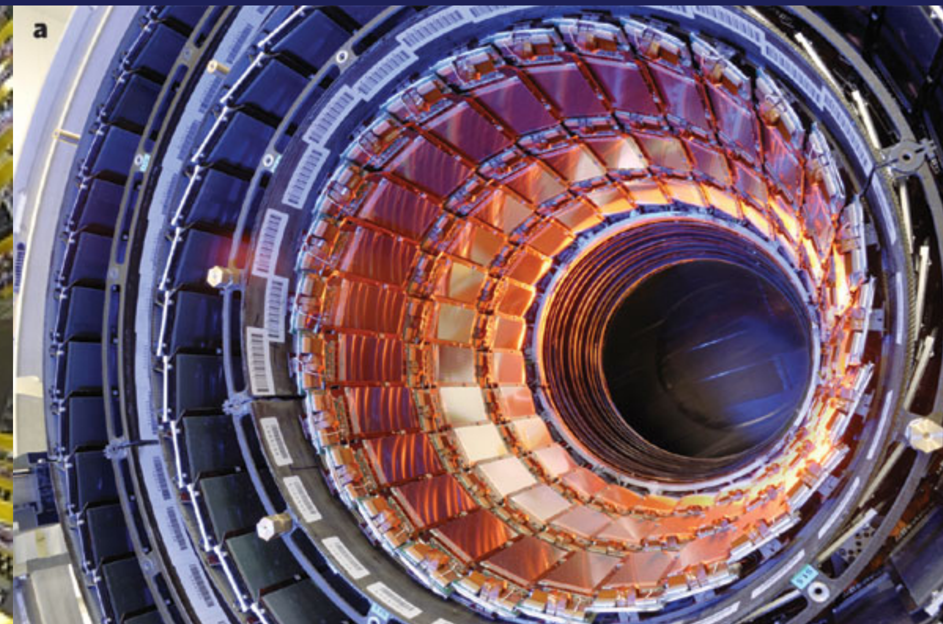
Particle Identification

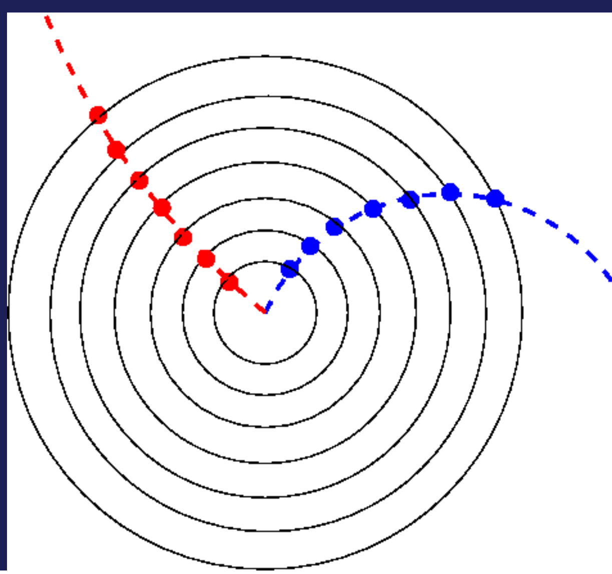
- Collisions enclosed by layers of different sub-detectors:
  - separate particle types
  - measure their energies and angles

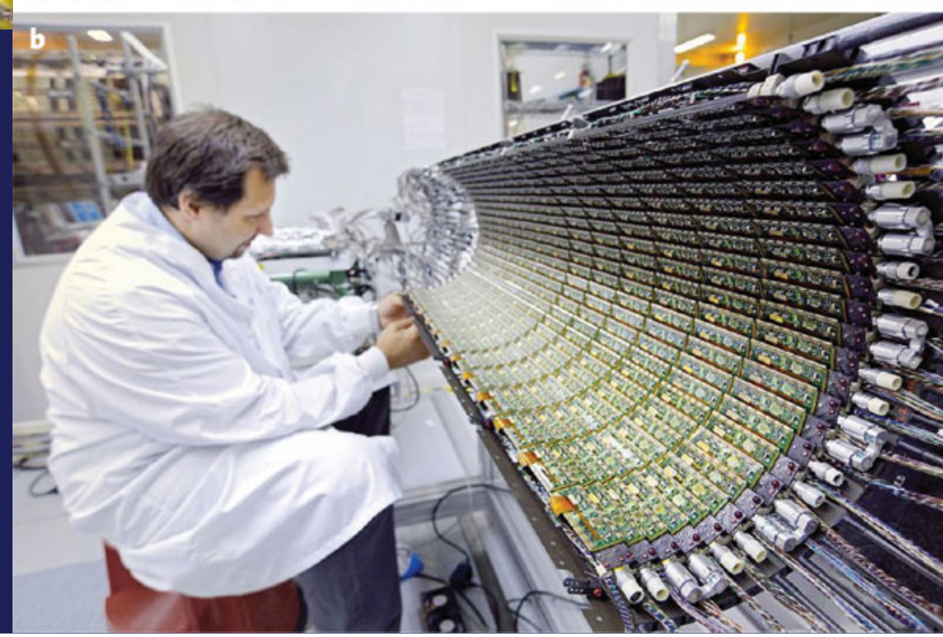


Tracking Detectors









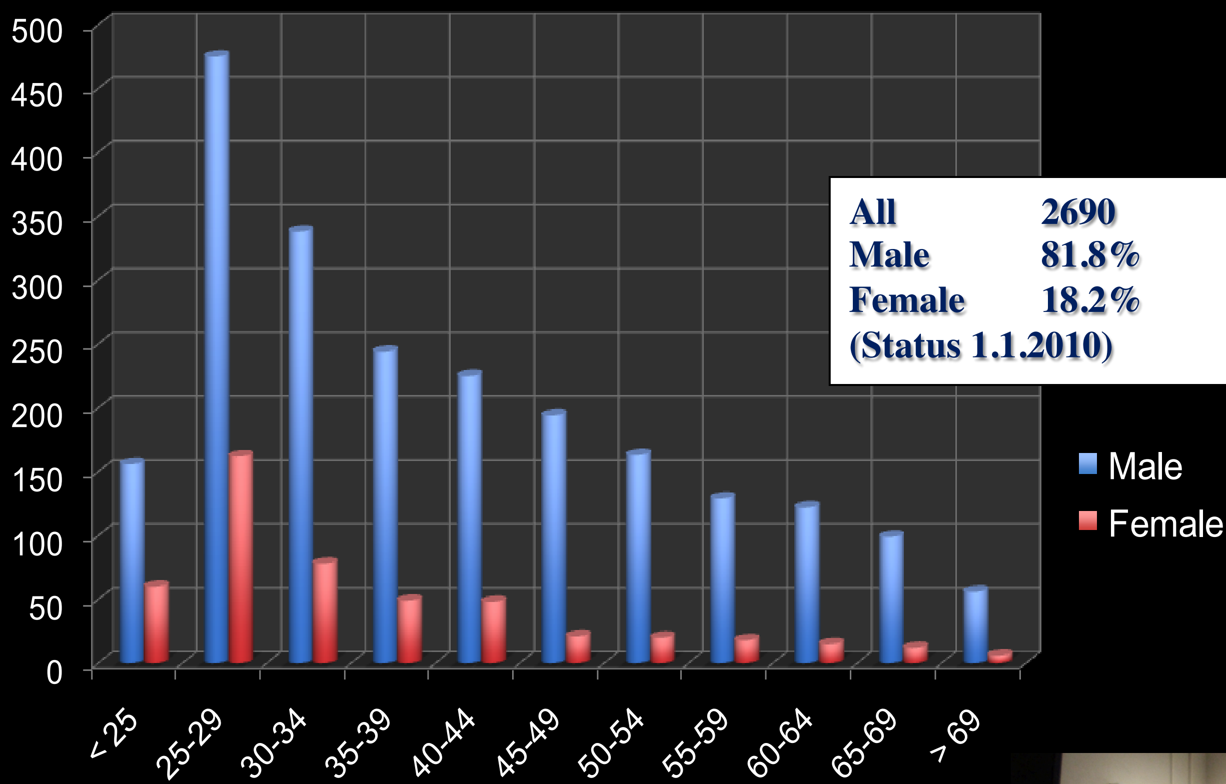
ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

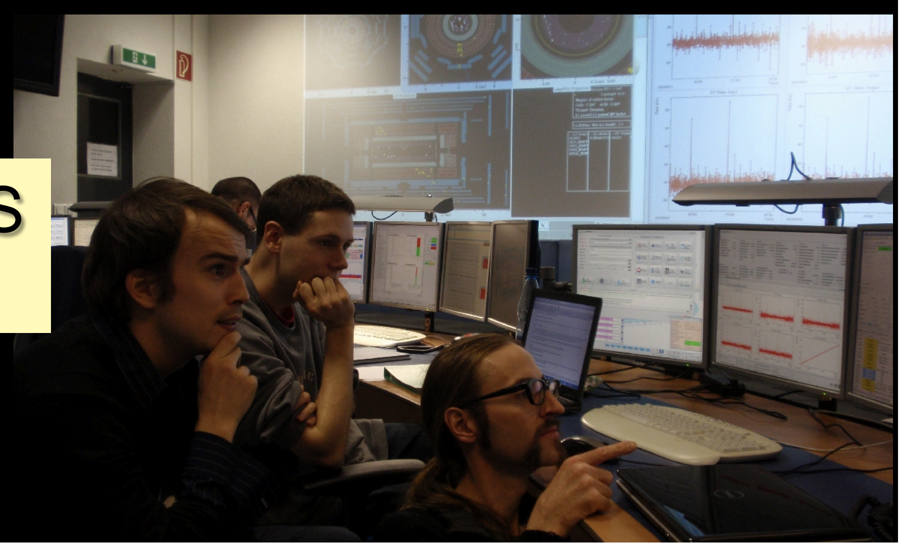
founded in 1992

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Age and Gender Profile of ATLAS



All	2690	(< 35 y	47.2%)
Male	81.8%	(< 35 y	44.0%)
Female	18.2%	(< 35 y	61.3%)
(Status 1.1.2010)			



NYU students in ATLAS control room

Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11254/s
#bunches: n_{bunch}=1368
#protons / bunch: $N_p = 1.5 \times 10^{11}$
Width of beams: $\sigma_x \approx \sigma_y \approx 15\ \mu m$

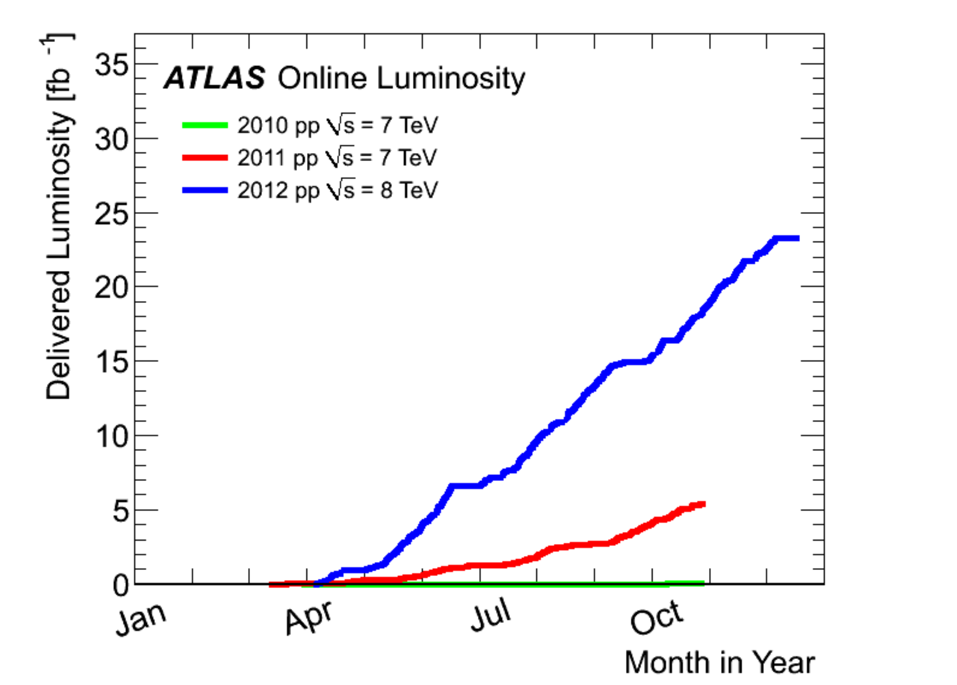
  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Cross section σ: Given by Nature (calc. by theorists)

Efficiency: optimized by experimentalist

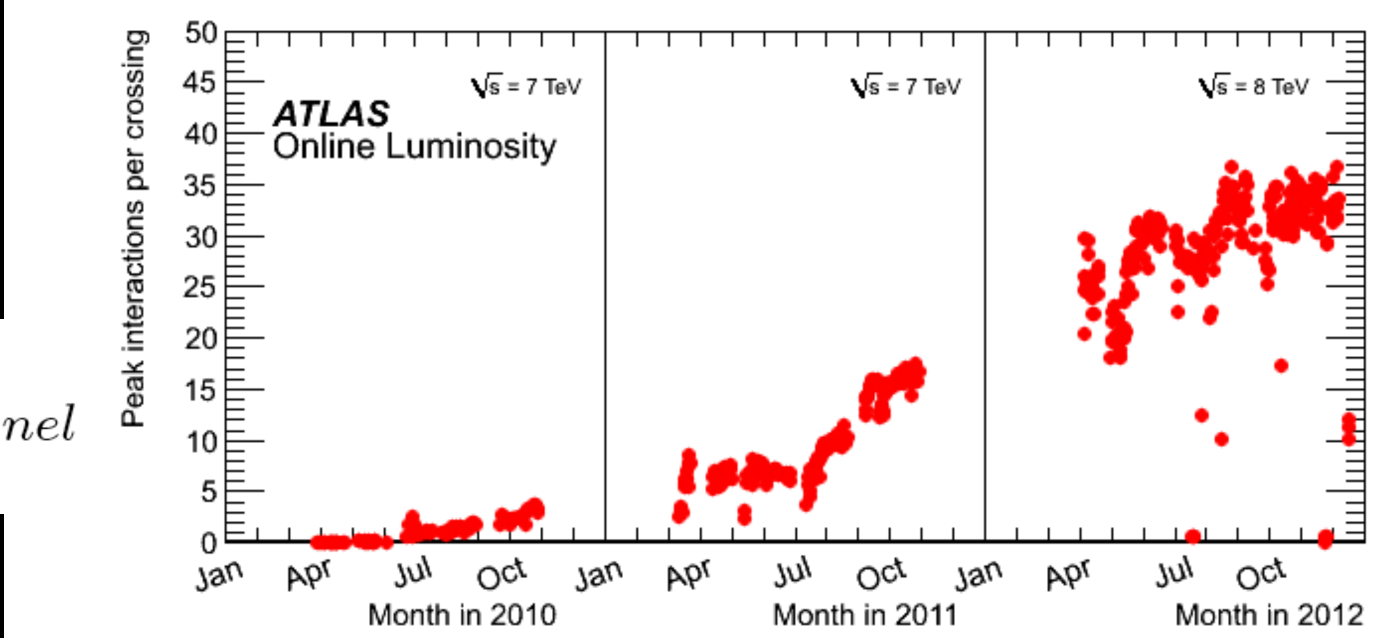
LHC Data Taking: 2010-2012

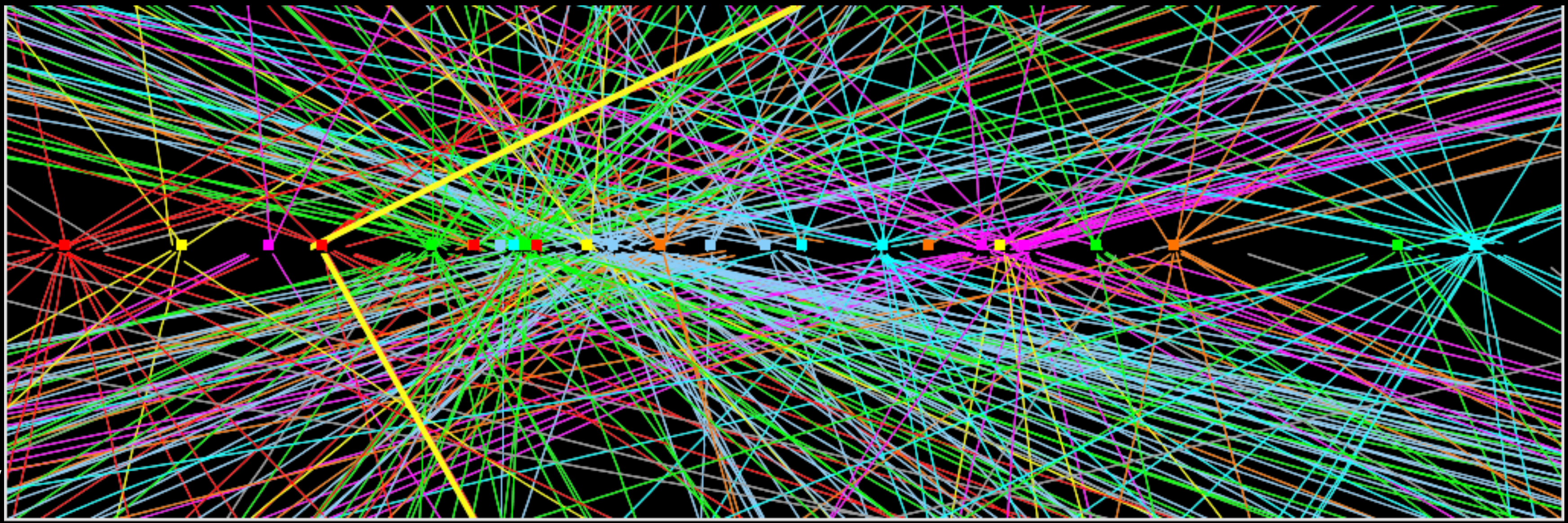


- Integrated L: 28 fb^{-1}
  - More than 2 x $L_{Tevatron}$
- Peak L: 7.7x10^{33} cm^{-2}s^{-1}
  - 20 million events/second
  - Write to disk: ~400 events/s
- Data Volume
  - 4x10^{9} events/year

The Price for high Luminosity: Pileup

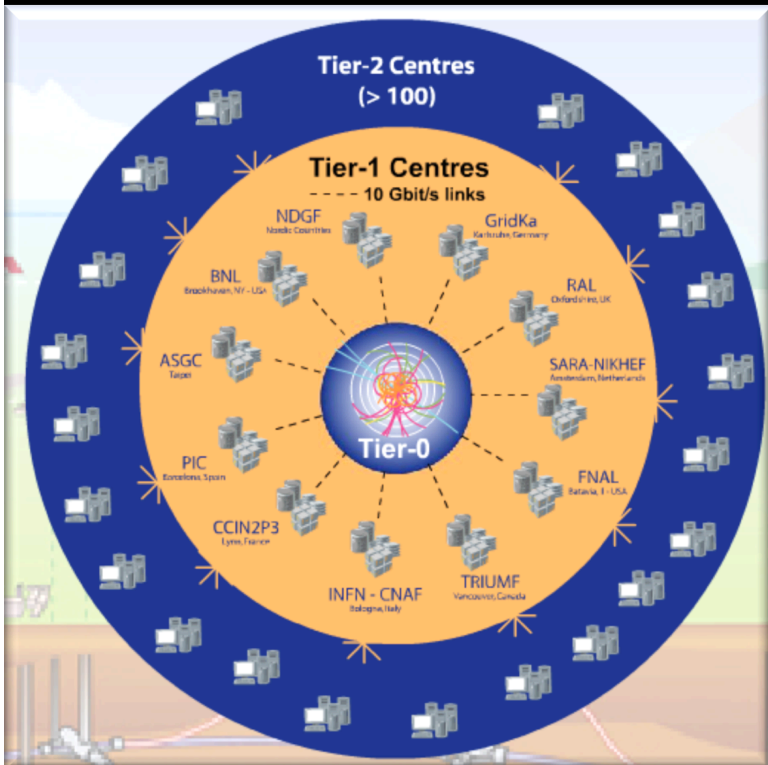
$$\mu = \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} \sigma_{inel}$$





Worldwide LHC Computing Grid

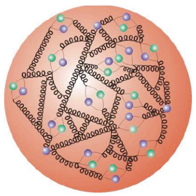
WLCG
Worldwide LHC Computing Grid

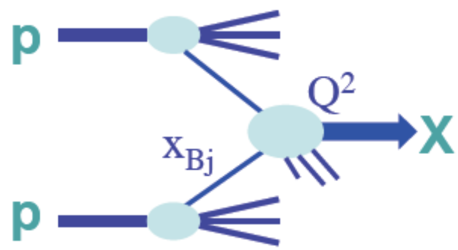


- Data volume: ~80 PB
  - LHC data
  - MC simulation
  - User data
- CPU time per event:
  - Reconstruction: ~15 seconds
  - Simulation: ~5 minutes
- Data analysis in
  - >100 computing centers

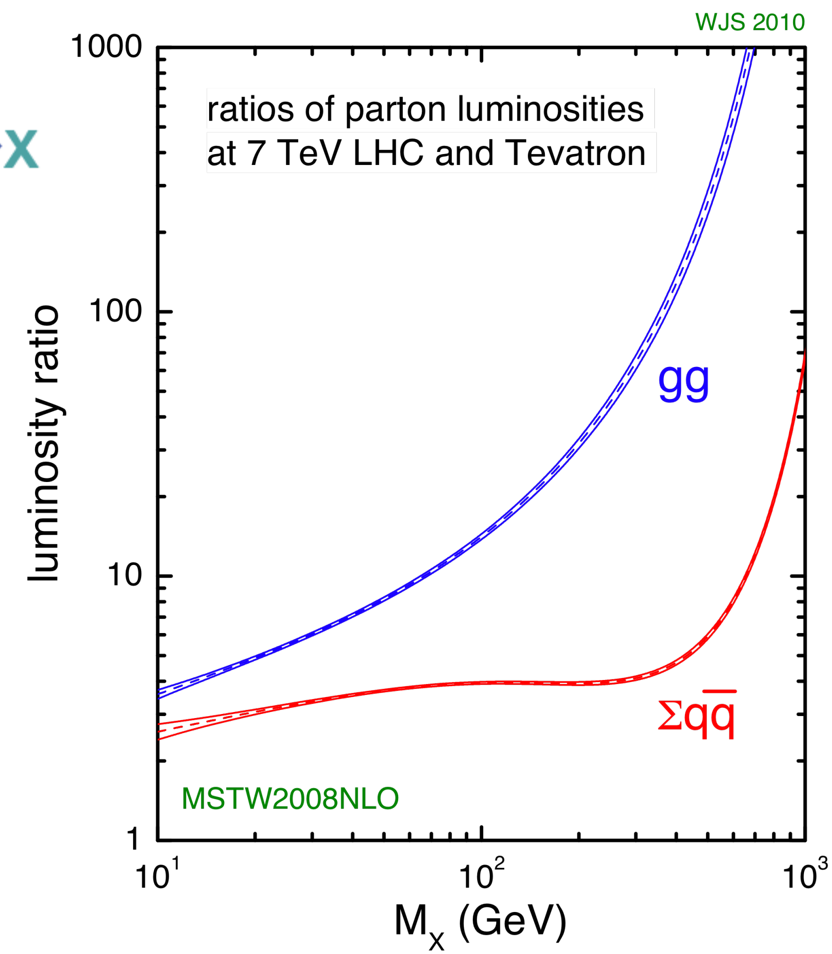
Physics Cross Sections

$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$



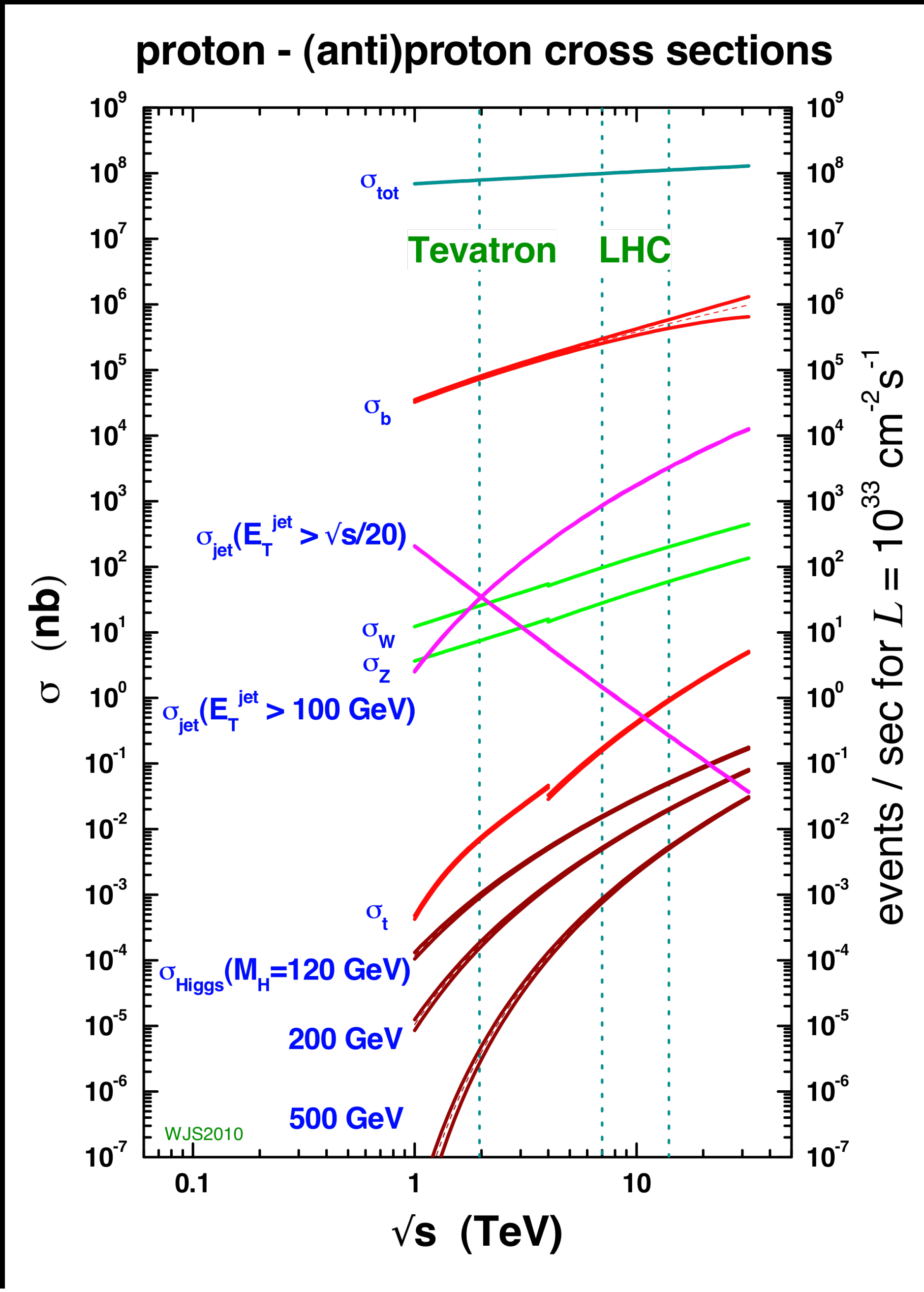


Process	M_X	σ(LHC @ 7 TeV) / σ(Tevatron)
$q\bar{q} \to W$	80 GeV	3
$q\bar{q} \to Z'_{SM}$	1 TeV	50
$gg \to H$	120 GeV	20
$q\bar{q}/gg \to t\bar{t}$	2x173 GeV	15
$gg \to \tilde{g}\tilde{g}$	2x400 GeV	1000



- $\int$Ldt=1 fb^{-1} at LHC competitive with 10 fb^{-1} at Tevatron for many processes

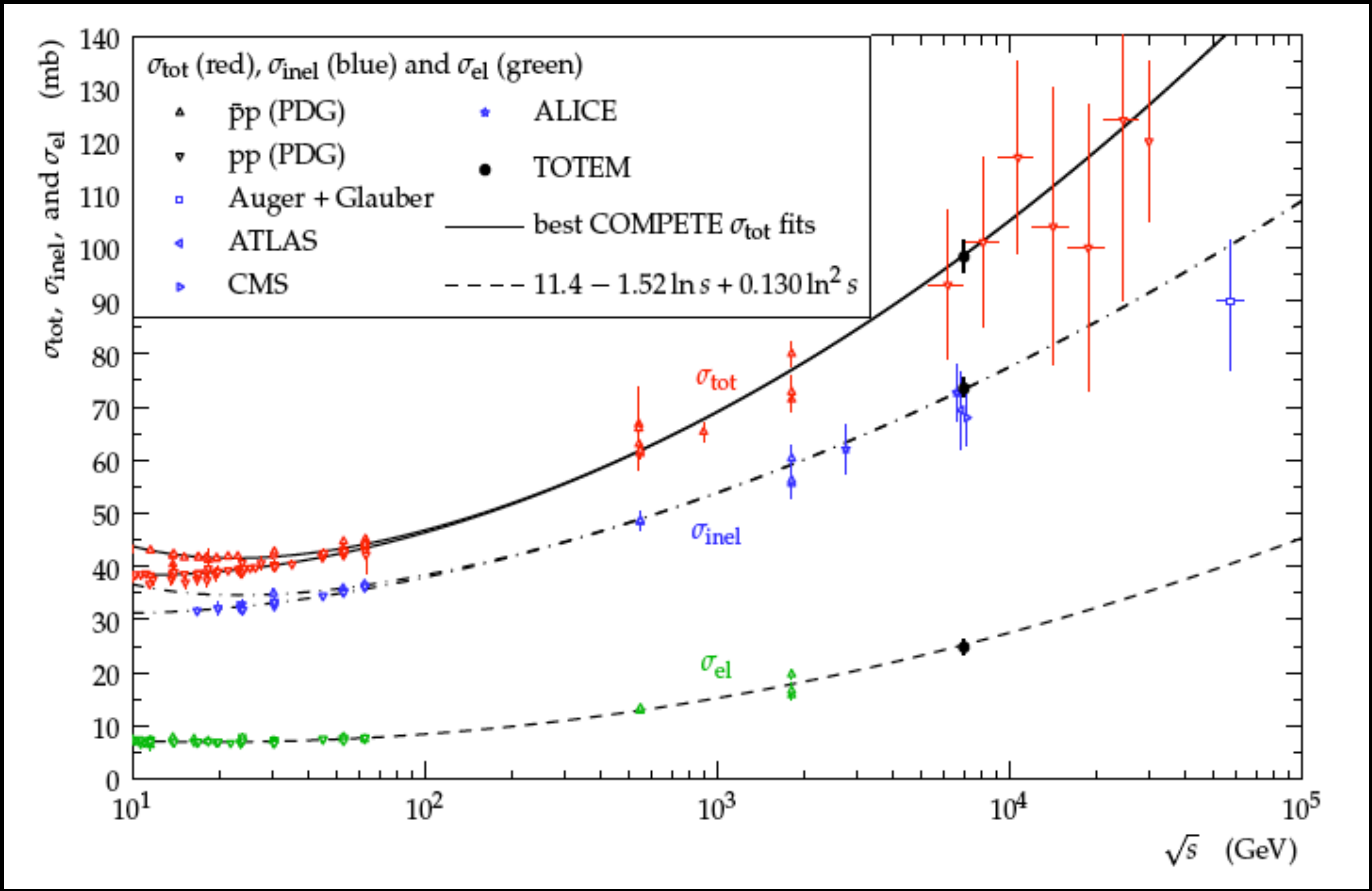
Physics Processes at the LHC



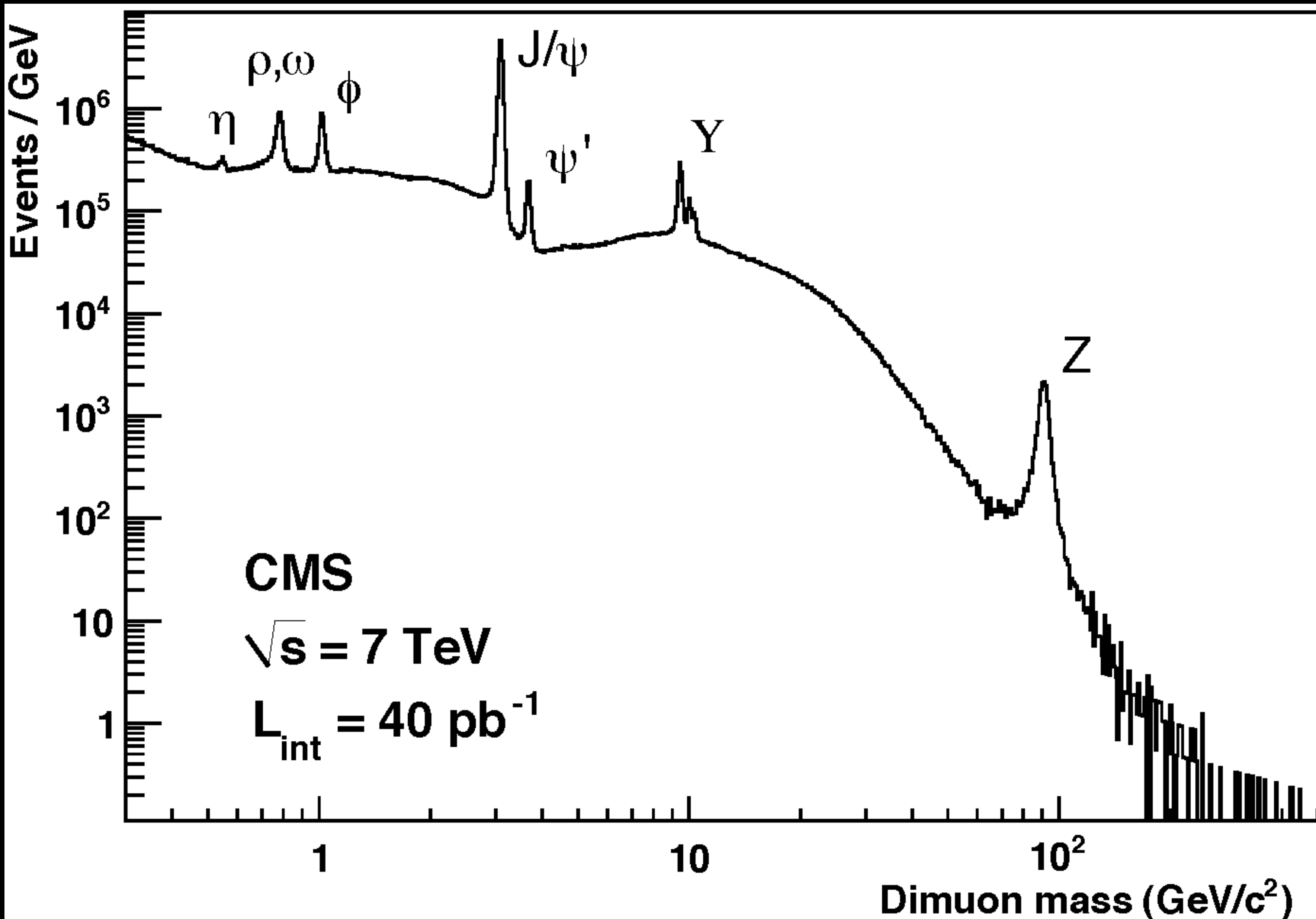
process	Rate at L_{peak} (Hz)
any interactions	10^9
Bottom quarks	10^6
Jets with p_T>100 GeV	10^4
W bosons	10^3
Z bosons	10^2
Top quarks	1
Higgs (M=125 GeV)	0.1
H->γγ (M=125 GeV)	$2x10^{-4}$

Standard Model Measurements

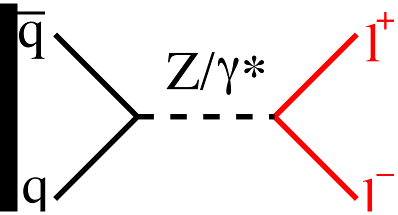
Total Cross Section: pp -> X



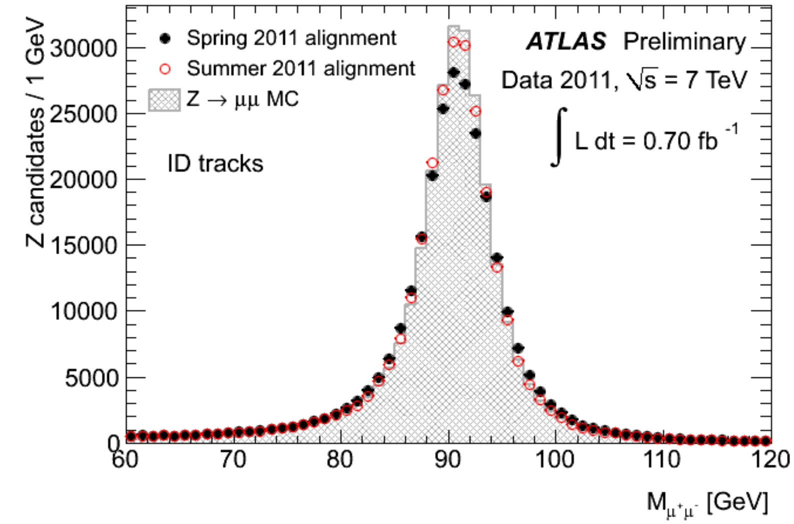
Dimuon Mass Spectrum

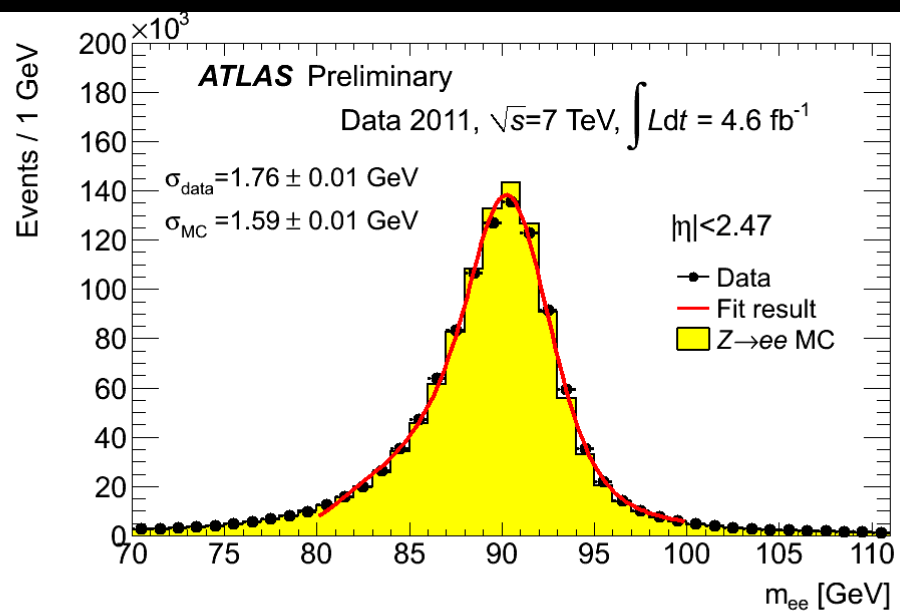


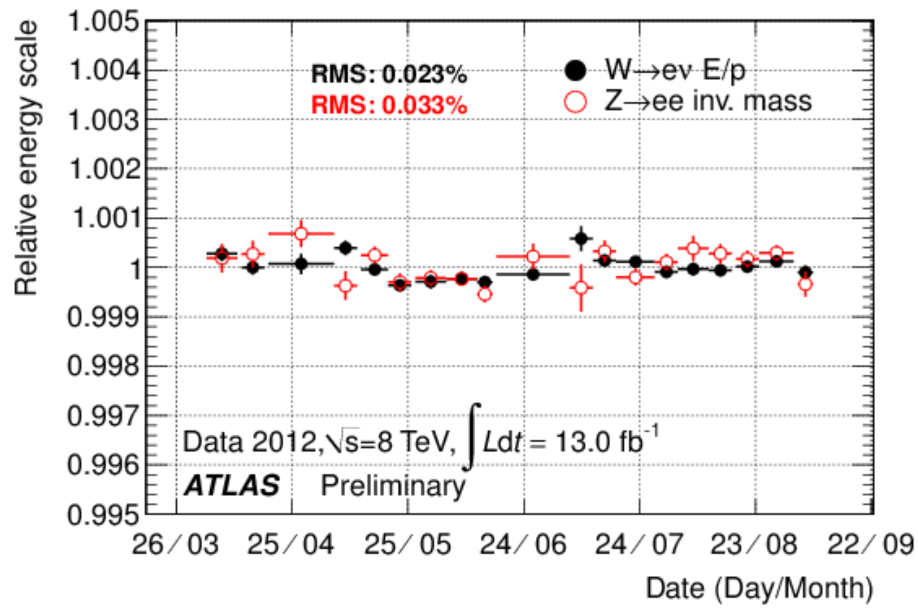
Z bosons

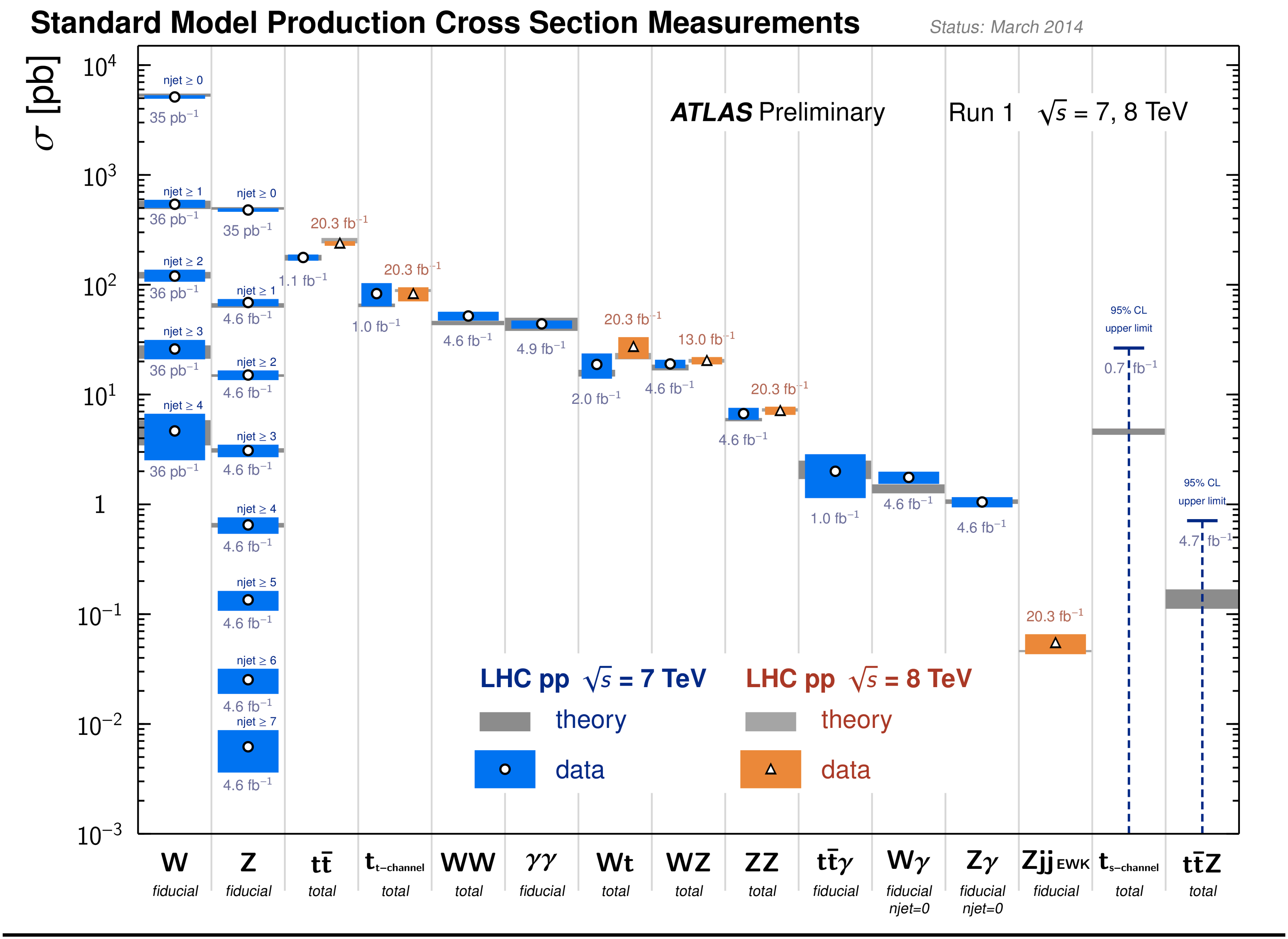


- Z boson used as calibration signal
  - electromagnetic calorimeter energy scale
  - muon momentum scale
  - many efficiencies
  - ….









Standard Model Production Cross Section Measurements
Status: March 2014
σ [pb]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
njet ≥ 0
35 pb⁻¹
njet ≥ 1
36 pb⁻¹
njet ≥ 2
36 pb⁻¹
njet ≥ 3
36 pb⁻¹
njet ≥ 4
36 pb⁻¹
4.6 fb⁻¹
1.1 fb⁻¹
20.3 fb⁻¹
1.0 fb⁻¹
4.9 fb⁻¹
2.0 fb⁻¹
13.0 fb⁻¹
95% CL upper limit
0.7 fb⁻¹
4.7 fb⁻¹
LHC pp √s = 7 TeV
theory
data
LHC pp √s = 8 TeV
theory
data
W fiducial
Z fiducial
tt̄ total
t t-channel total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
tt̄γ fiducial
Wγ fiducial njet=0
Zγ fiducial njet=0
Zjj EWK fiducial
t s-channel total
tt̄Z total

The Higgs Boson Search

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

Nucl. Phys. **B106** (1976)

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Nucl. Phys. B**106** (1976)

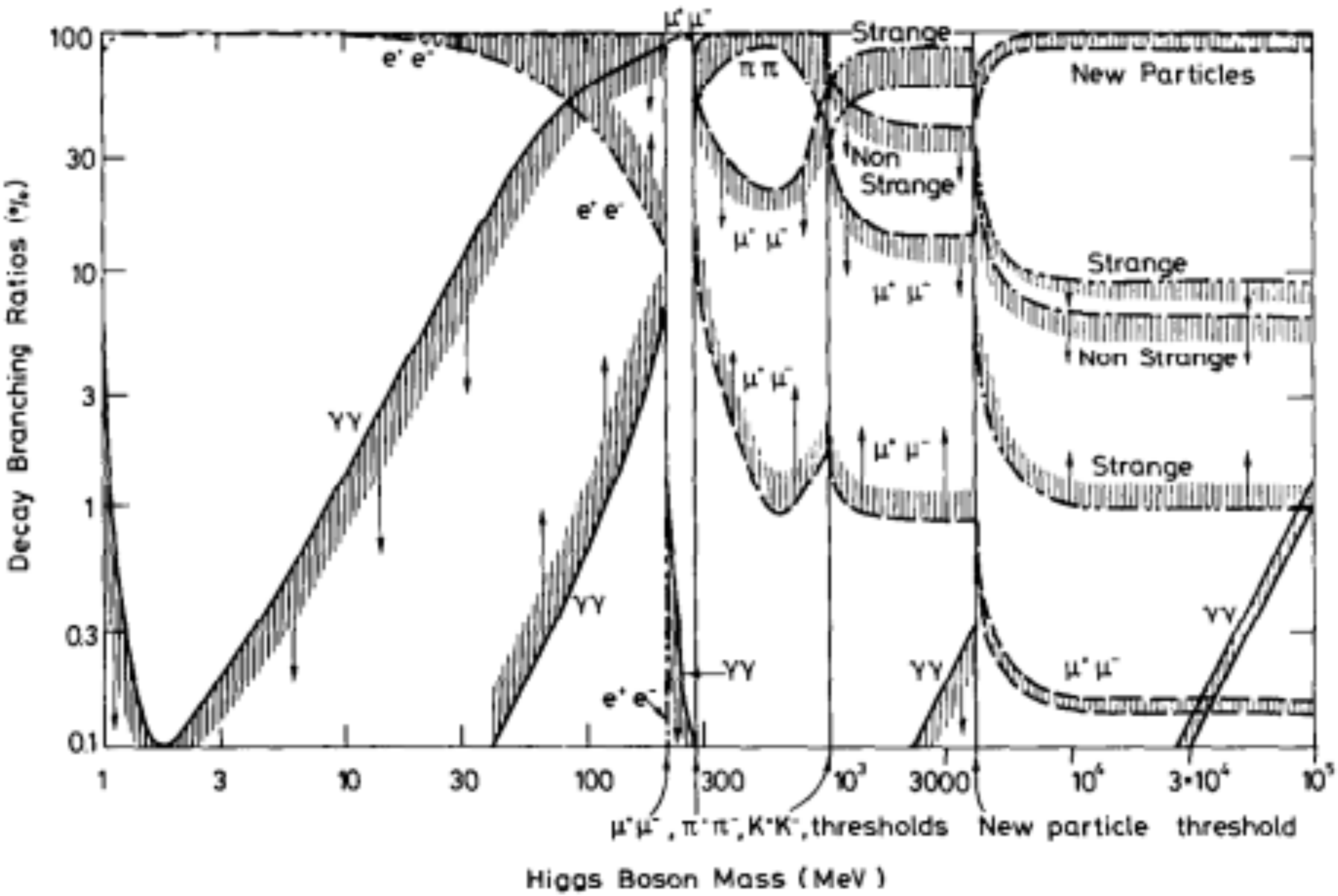
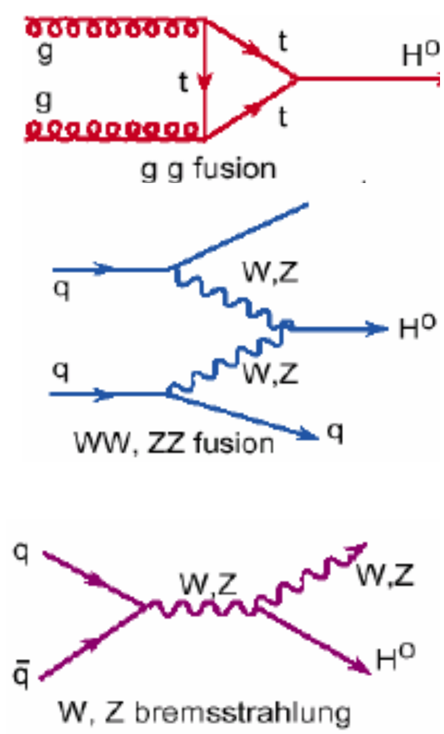
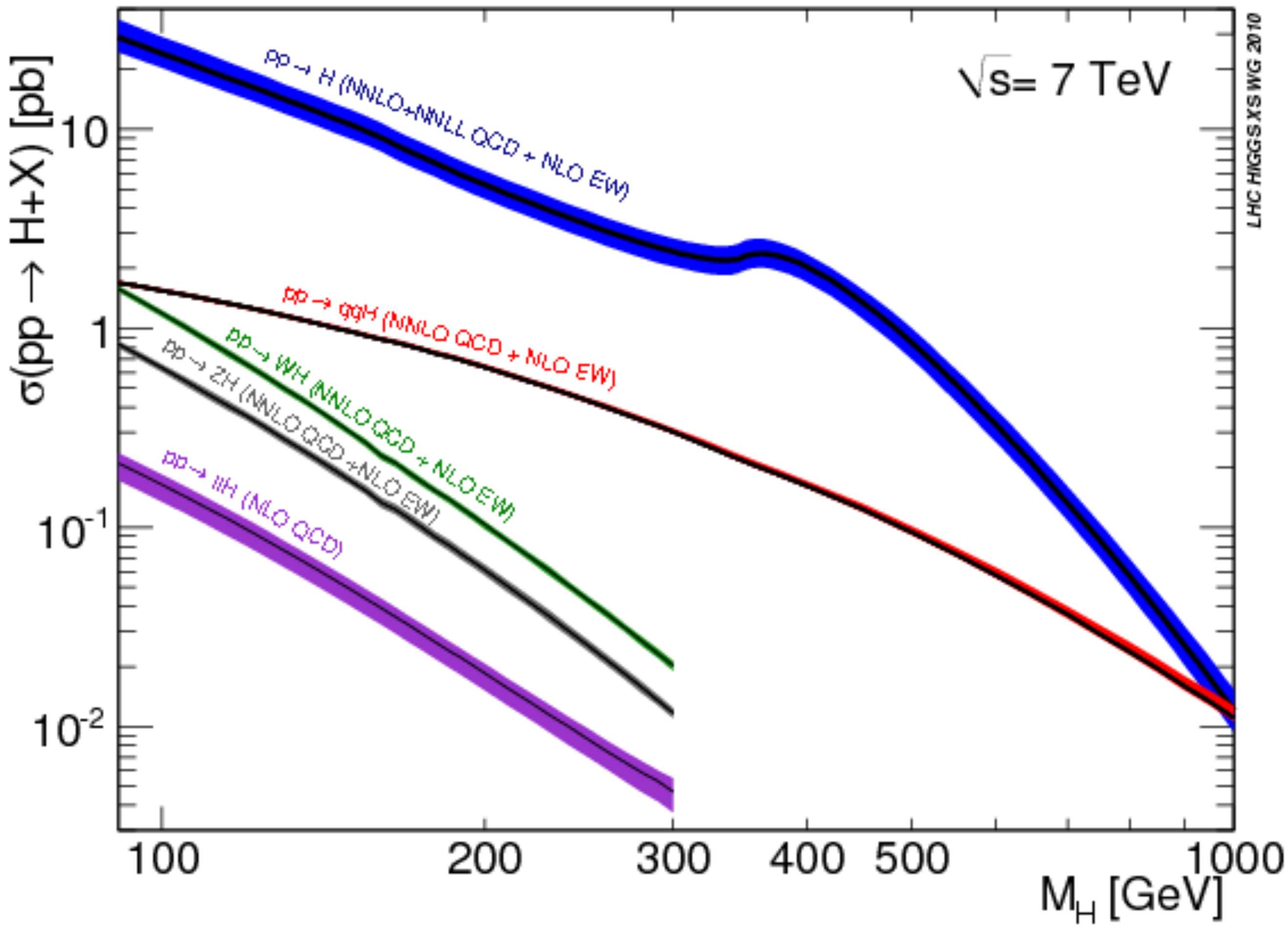


Fig. 1. Branching ratios of the Higgs boson for different values of its mass. The curves are calculated from the decay rates of sect. 4.

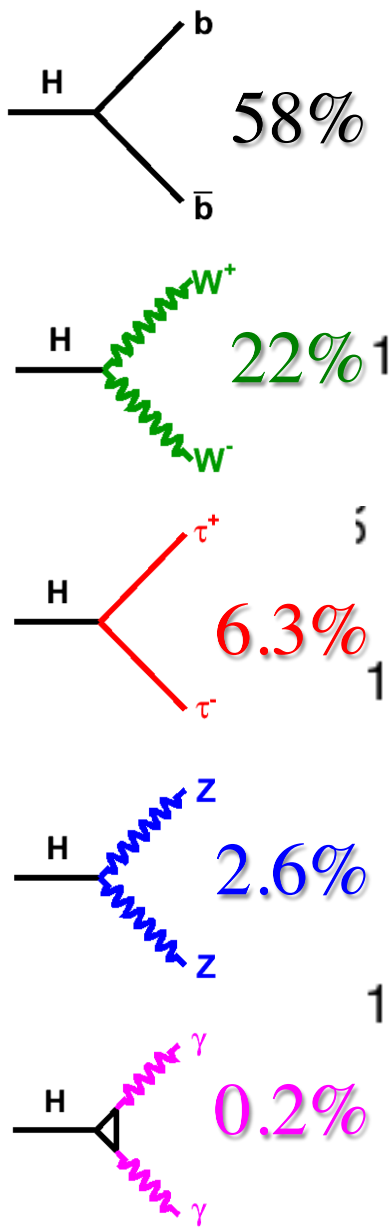
Higgs Boson Production

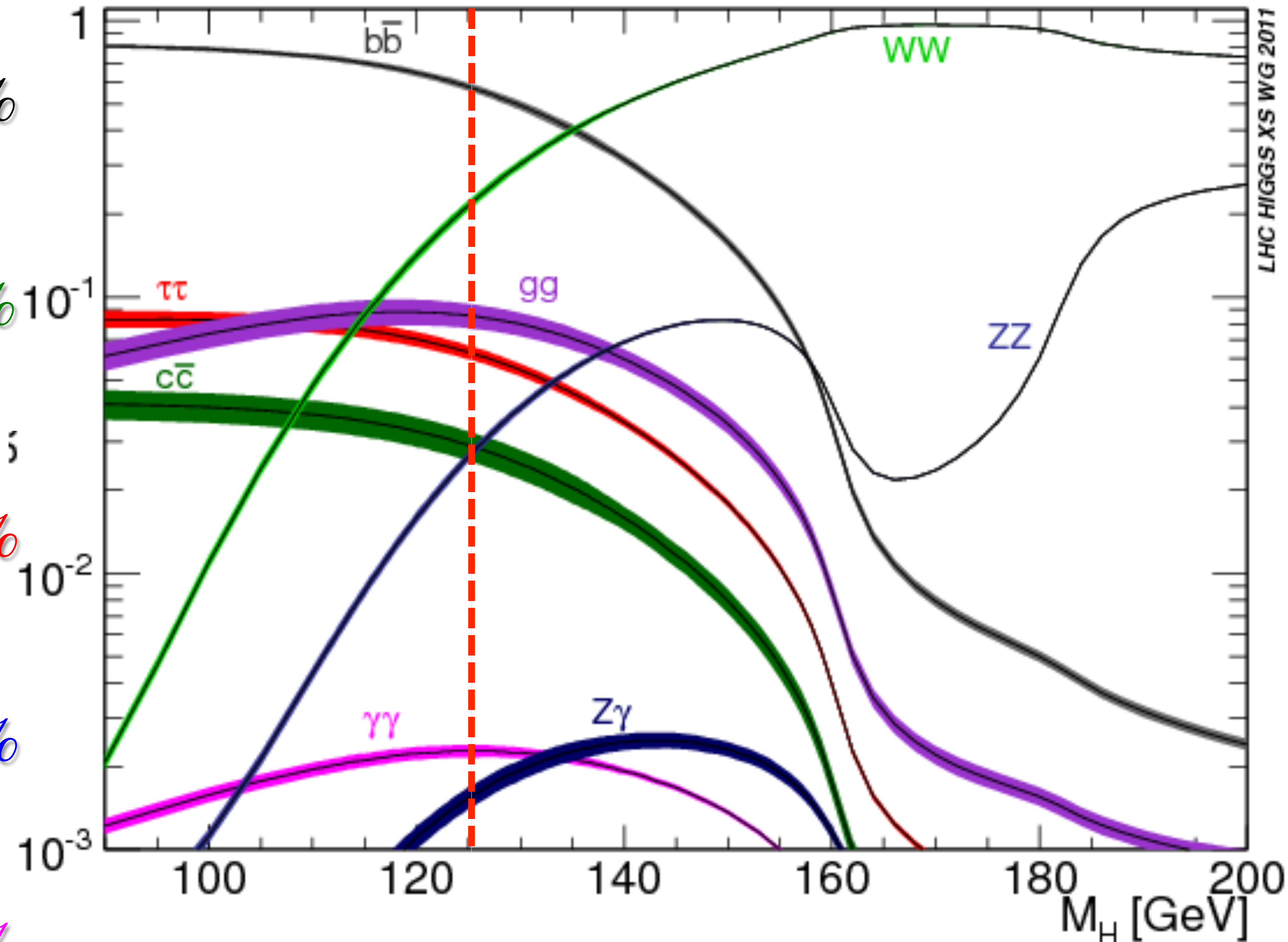




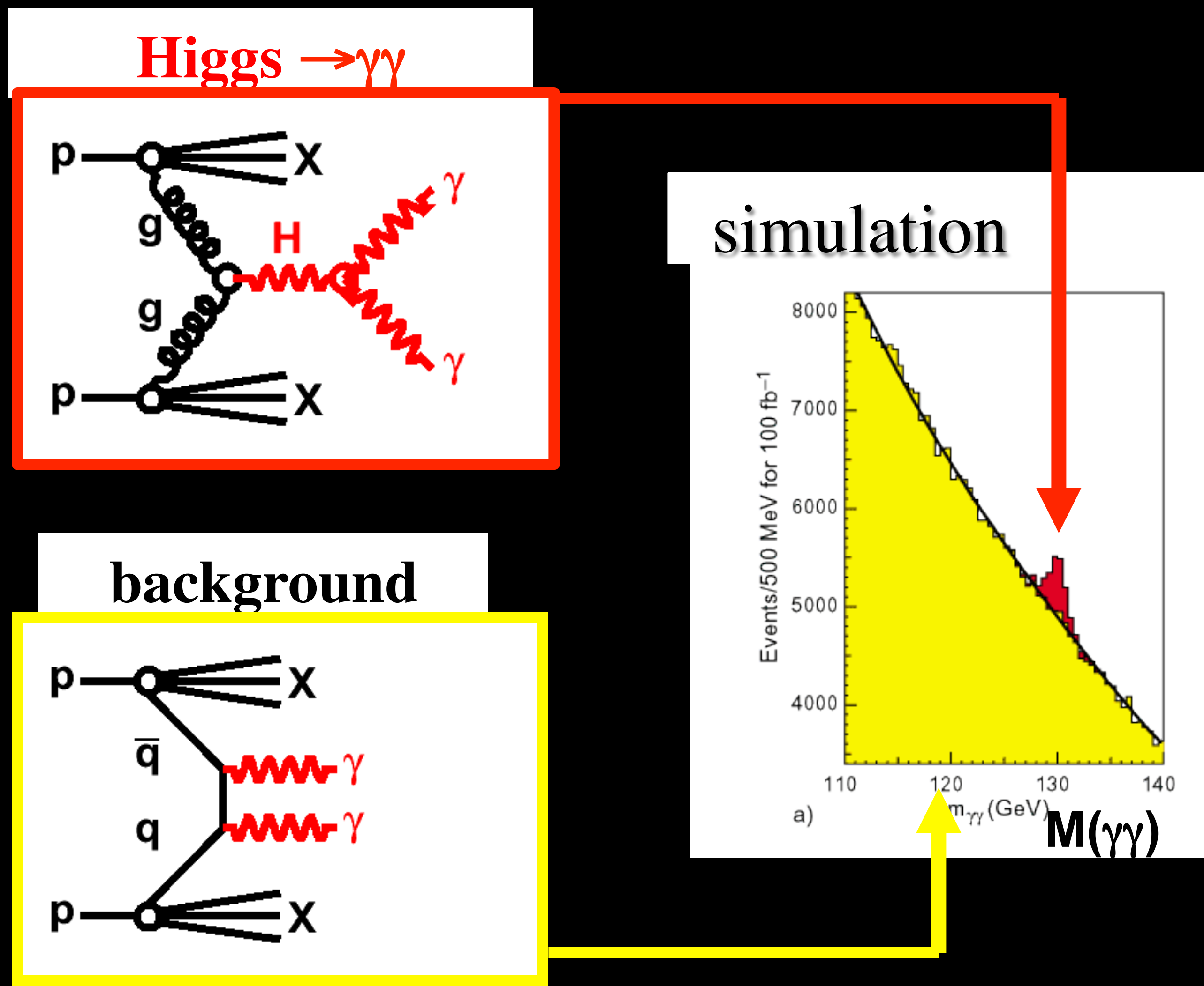
- Production rate known to ~10%
  - Various production mechanisms sensitive to different Higgs couplings (top quark versus W boson)

Higgs Boson Decay



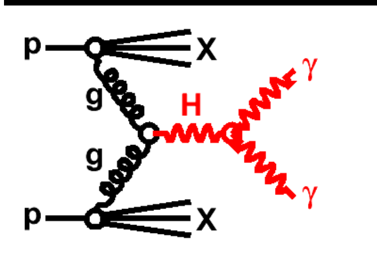


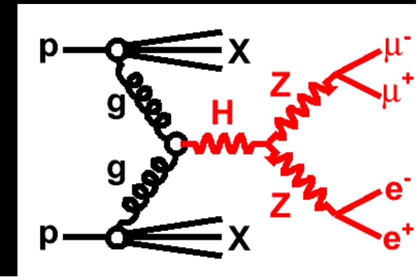
Finding the Higgs Boson (with photons)

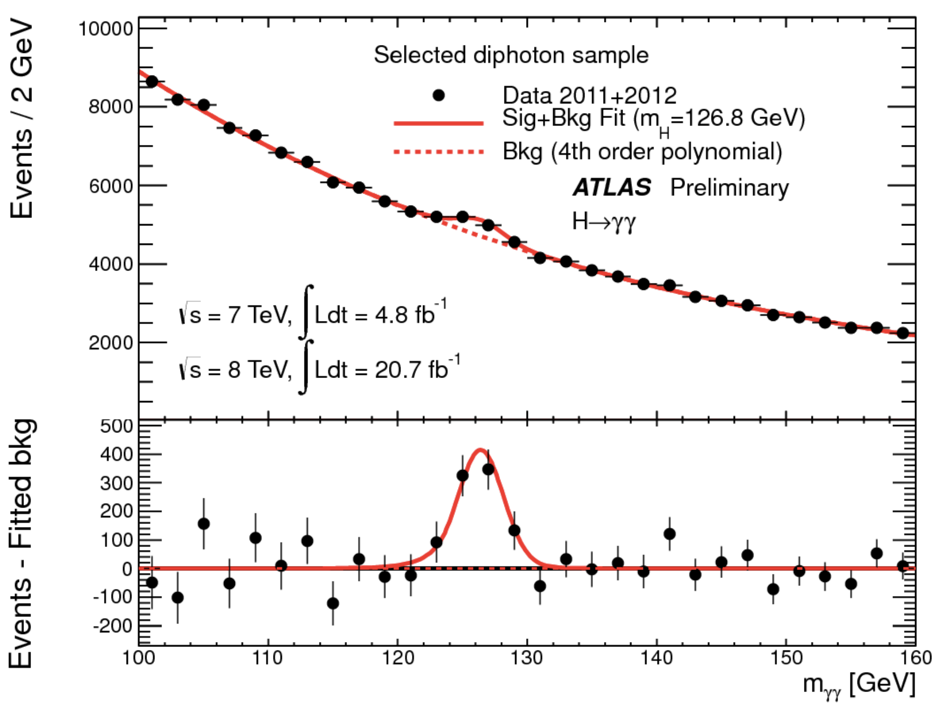


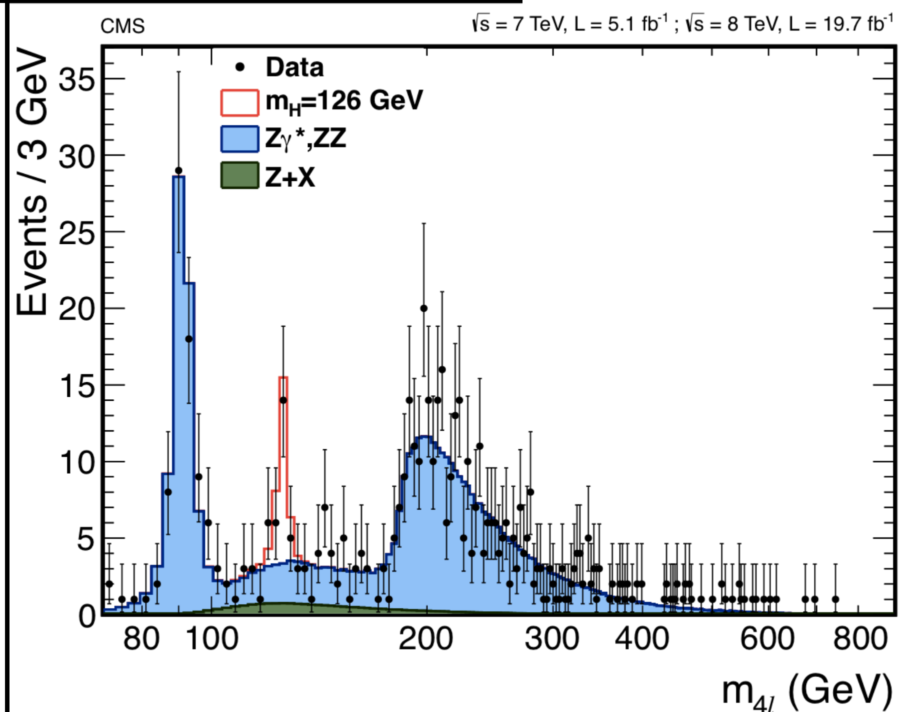
$$M_{Higgs} \approx M(\gamma\gamma) = 2\ E_1\ E_2\ (1\text{-}\cos\alpha)$$

Higgs Boson Discovery



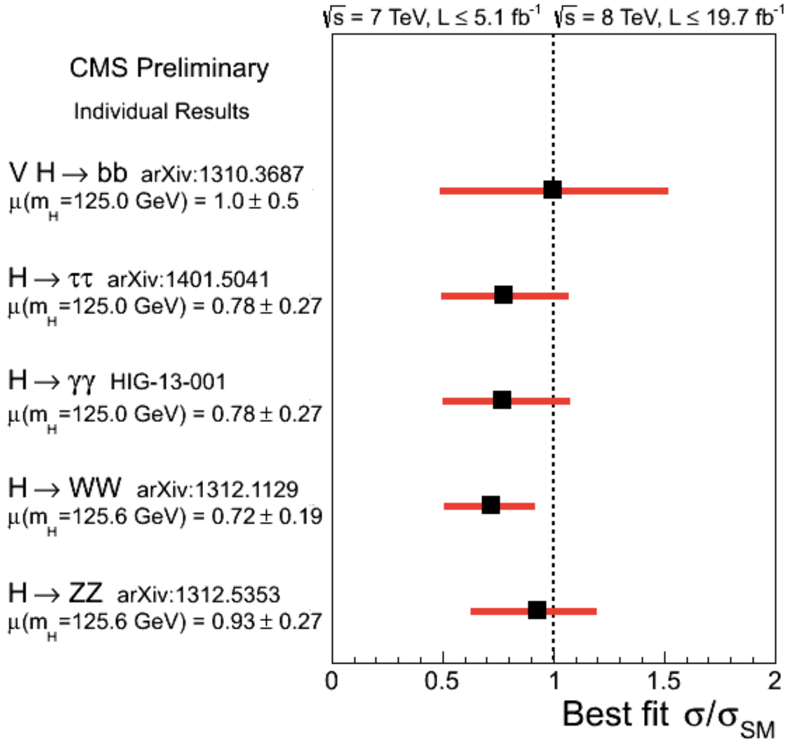


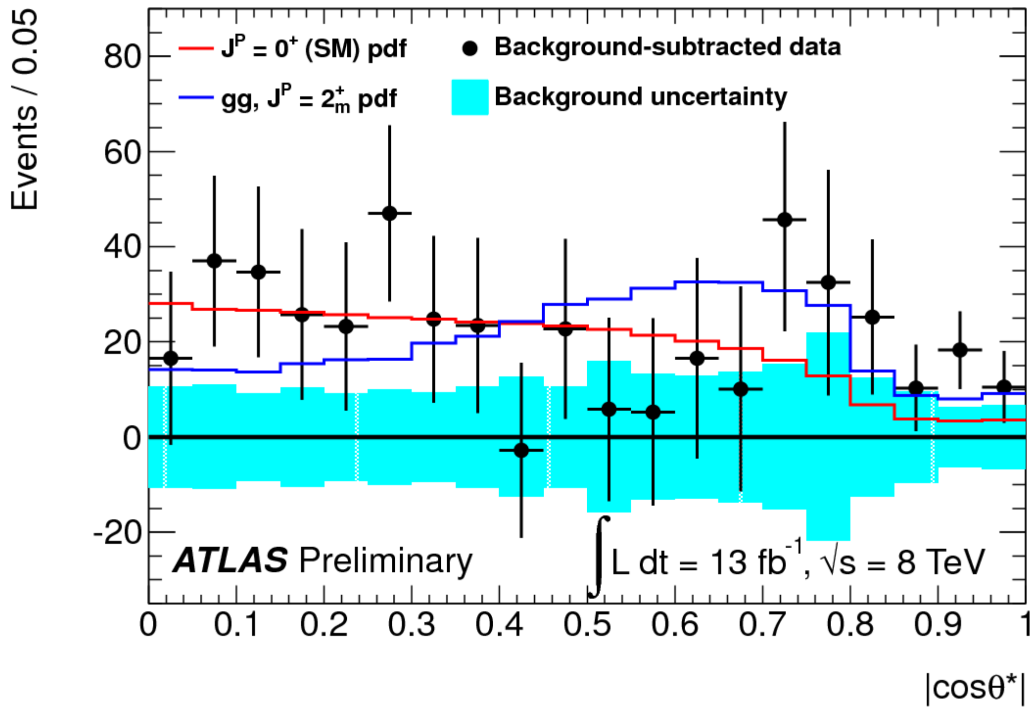




- Both experiments see narrow peak at ~125 GeV in two different decay channels

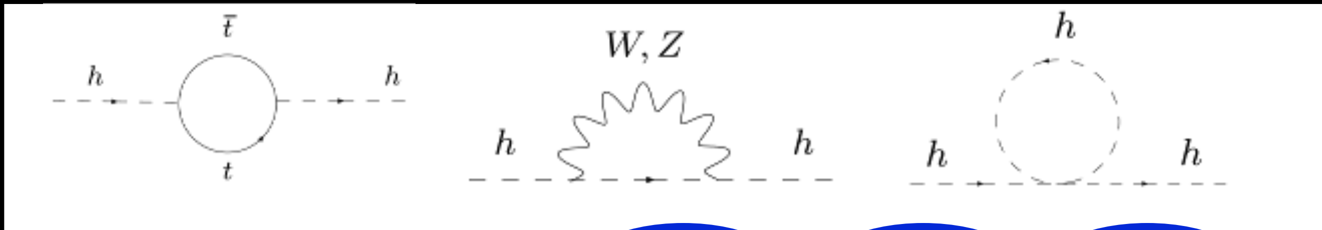
Is it the Standard Model Higgs boson?





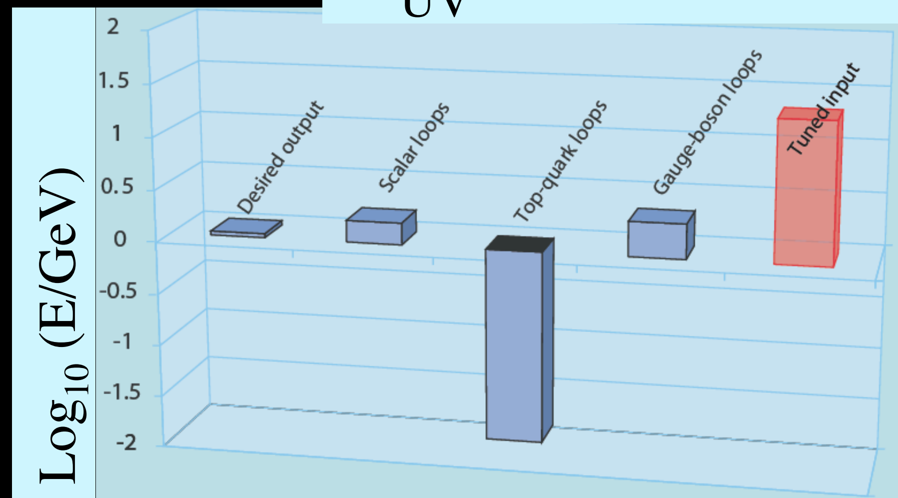
- spin and parity consistent with 0+
- Decay rates consistent with SM prediction
  - Within current uncertainties of 20-50%

Hierarchy Problem



$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$

Λ_{UV}=5 TeV



- Free parameter $m_H{}^{tree}$ "finetuned" to cancel huge corrections

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ...].$$

- Huge puzzle to theorists since >20 years
- Can only be solved by new physics at the TeV scale
  - 1000s of papers (e.g. by N. Weiner, J. Ruderman,…)

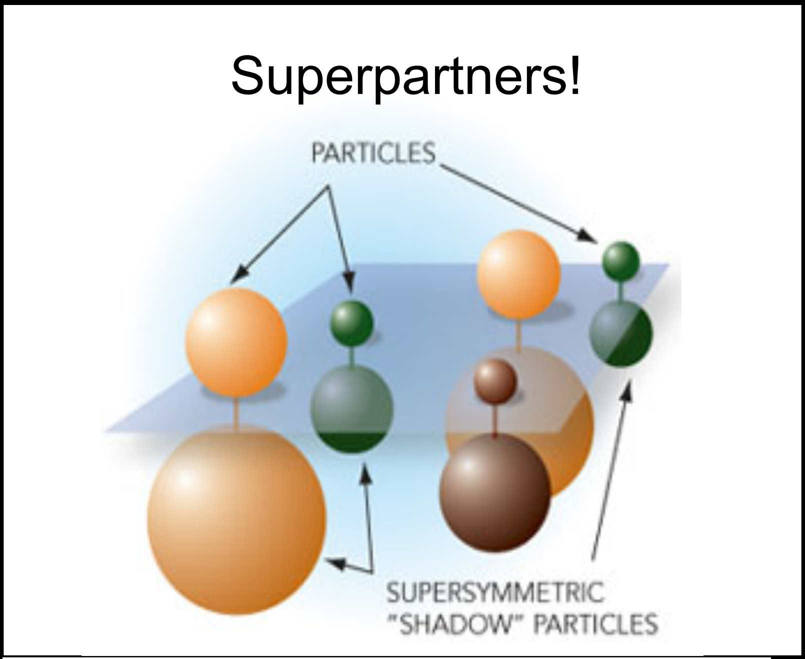
Solving the hierarchy problem

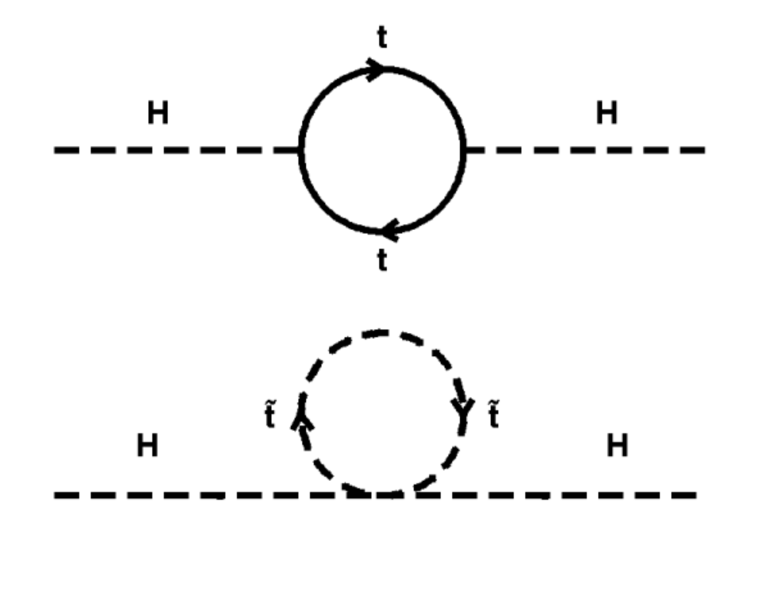
- "Supersymmetric" particles
  - Each SM particle has a partner with different spin, e.g.:

SM	spin	SUSY	spin
electron	1/2	selectron	0
top	1/2	stop	0
gluon	1	gluino	1/2

  - SUSY loops cancel SM loops
    - Size of loops naturally the same IF particle masses similar

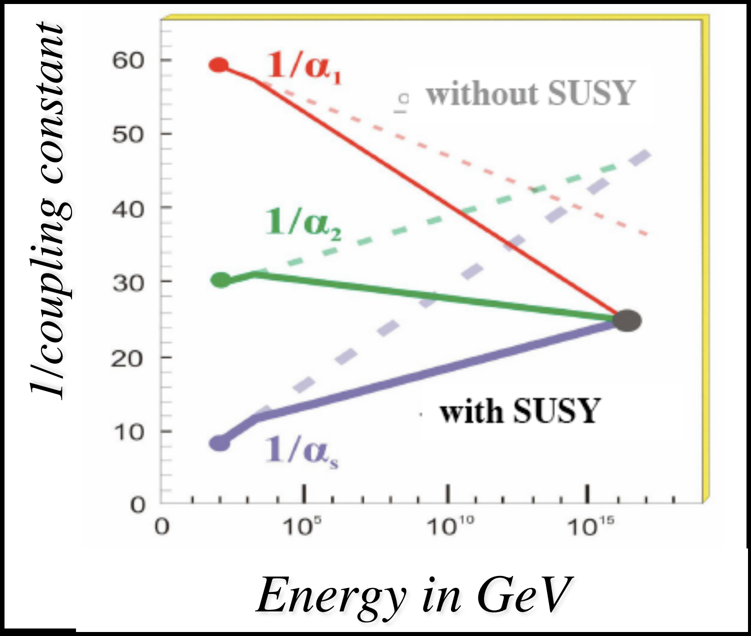
    => SUSY particles should be found at the LHC
  - No (or little) tuned ad-hoc parameters needed



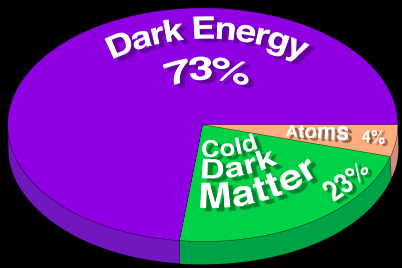


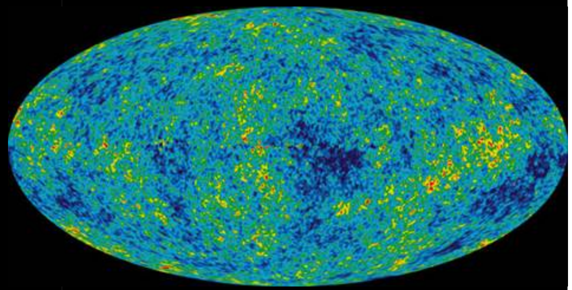
More virtues of Supersymmetry (SUSY)

- Electromagnetic, strong and weak force unify!
  - Miss unification in SM (barely)
  - Unify in SUSY if masses below ~100 TeV!

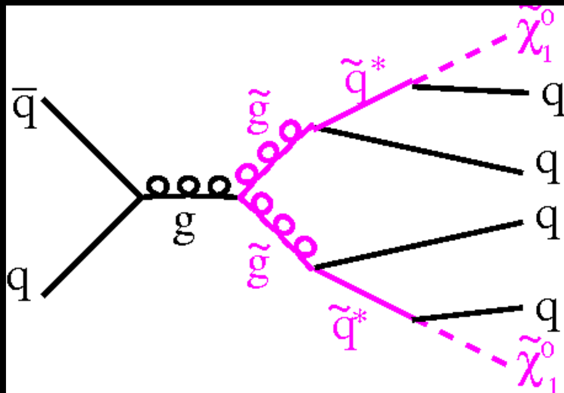


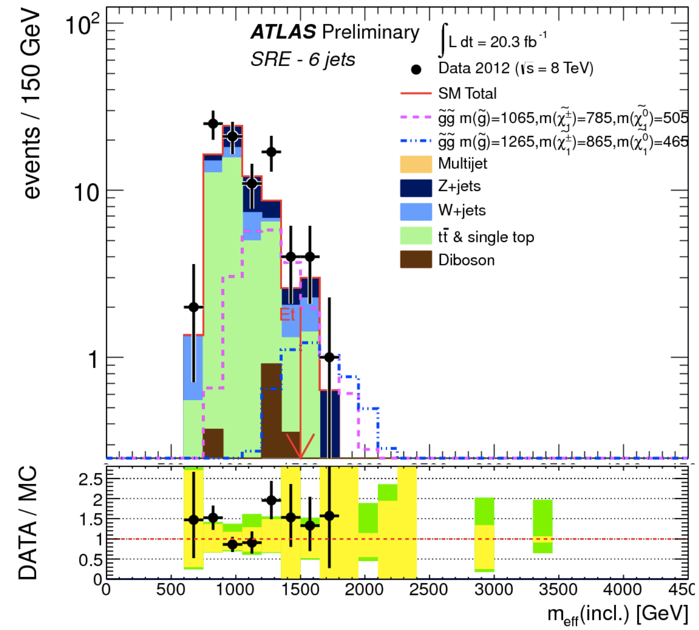
- Provides candidate for dark matter with mass ~ 0.1-1 TeV
  - Lightest SUSY particle, typically the “neutralino”



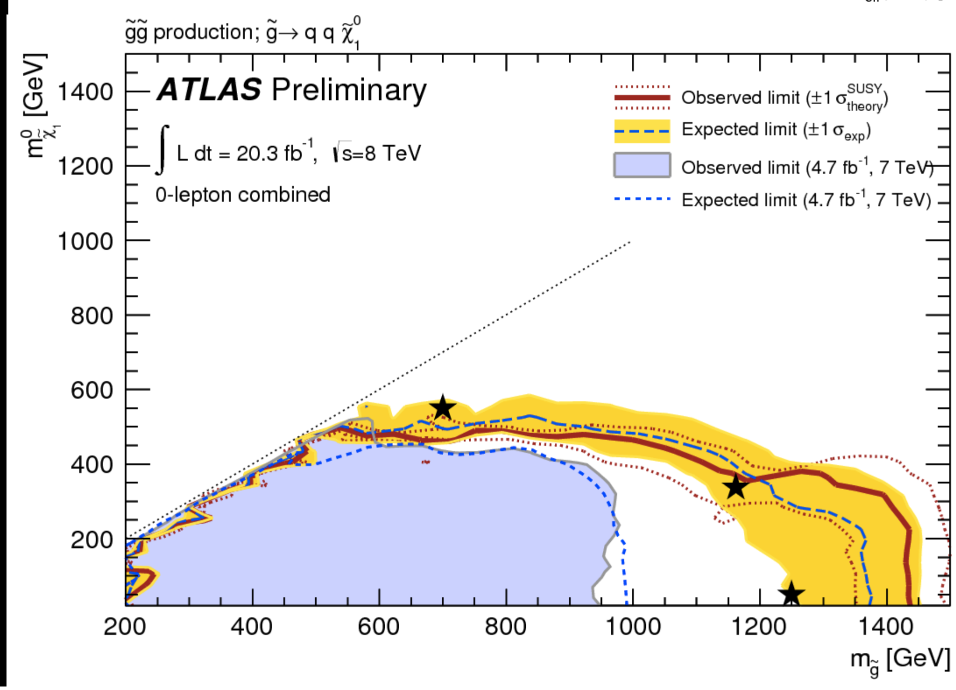


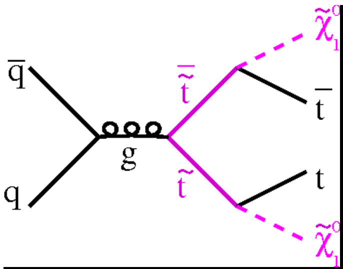
SUSY Search: Jets + Missing E_T





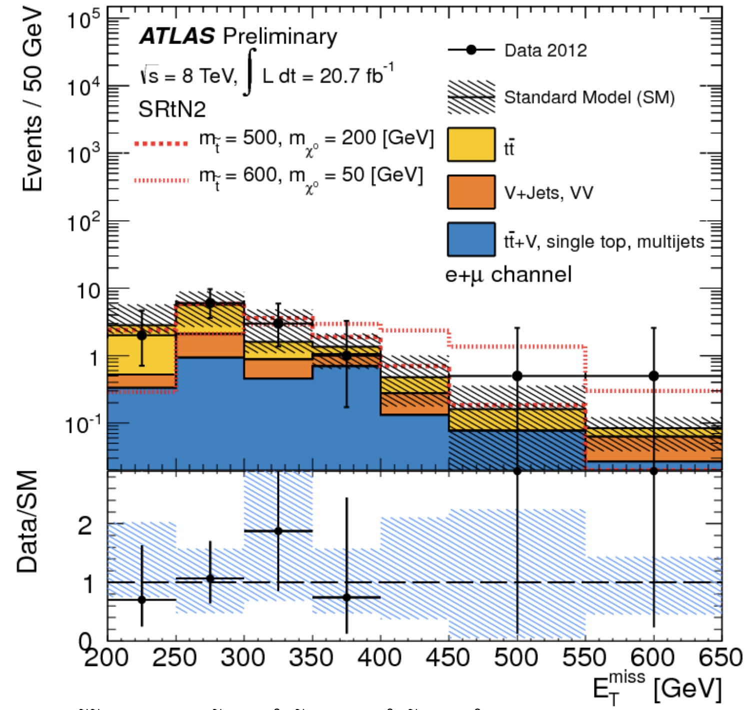
- Jets result from cascade decays of squarks and gluinos
- Excludes gluinos with m<1.4 TeV assuming
  - – squarks all have similar masses
  - – LSP mass < 400 GeV

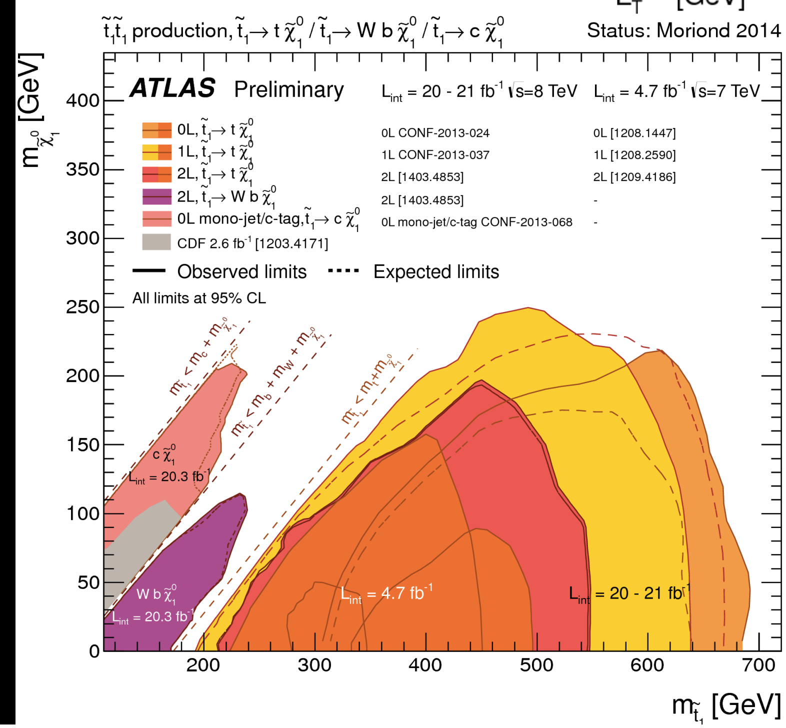




Stop quark

- Stop quark required to be light to solve hierarchy problem
  - search done in many possible decay channels
- M(stop)<600 GeV excluded for LSP masses below ~200 GeV
  - Many caveats though as statement depends on other SUSY parameters

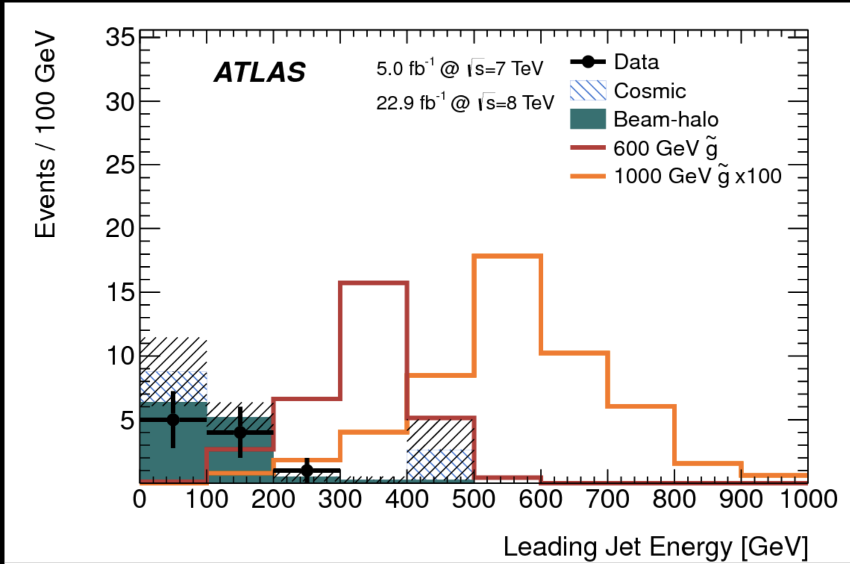


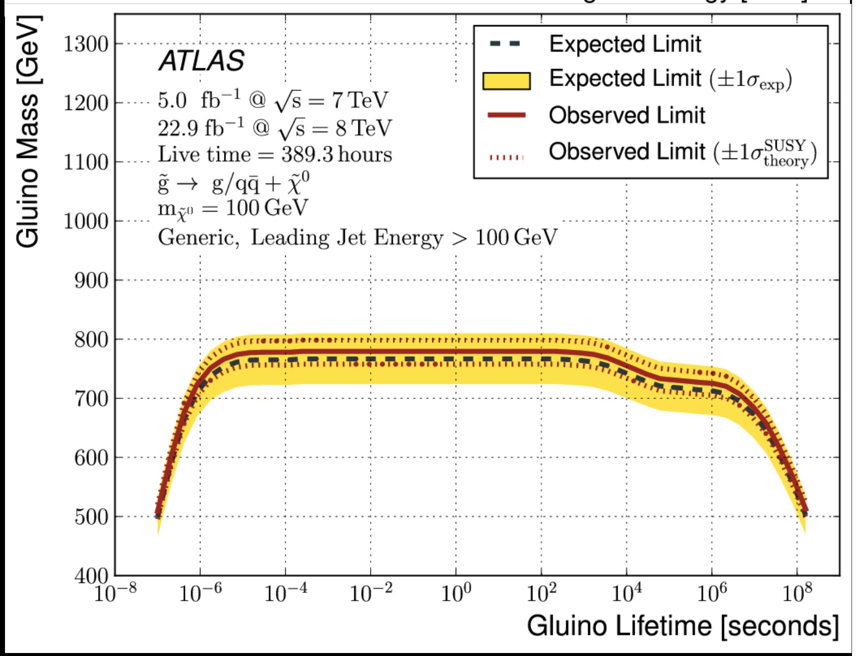


Split SUSY

Arkani-Hamed, Dimopoulos '02

- Give up on solving hierarchy problem
  - Still want Dark Matter candidate and unification
  - Squarks and sleptons heavy but gauginos and gluino light
- Could result in meta-stable gluinos (e.g. lifetime>1 μs)
  - Get stuck in calorimeter and decay unrelated to any beam crossing
  - Analysis pioneered and led by Andy Haas





Gluinos excluded up to 800 GeV

Summary of ATLAS SUSY Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

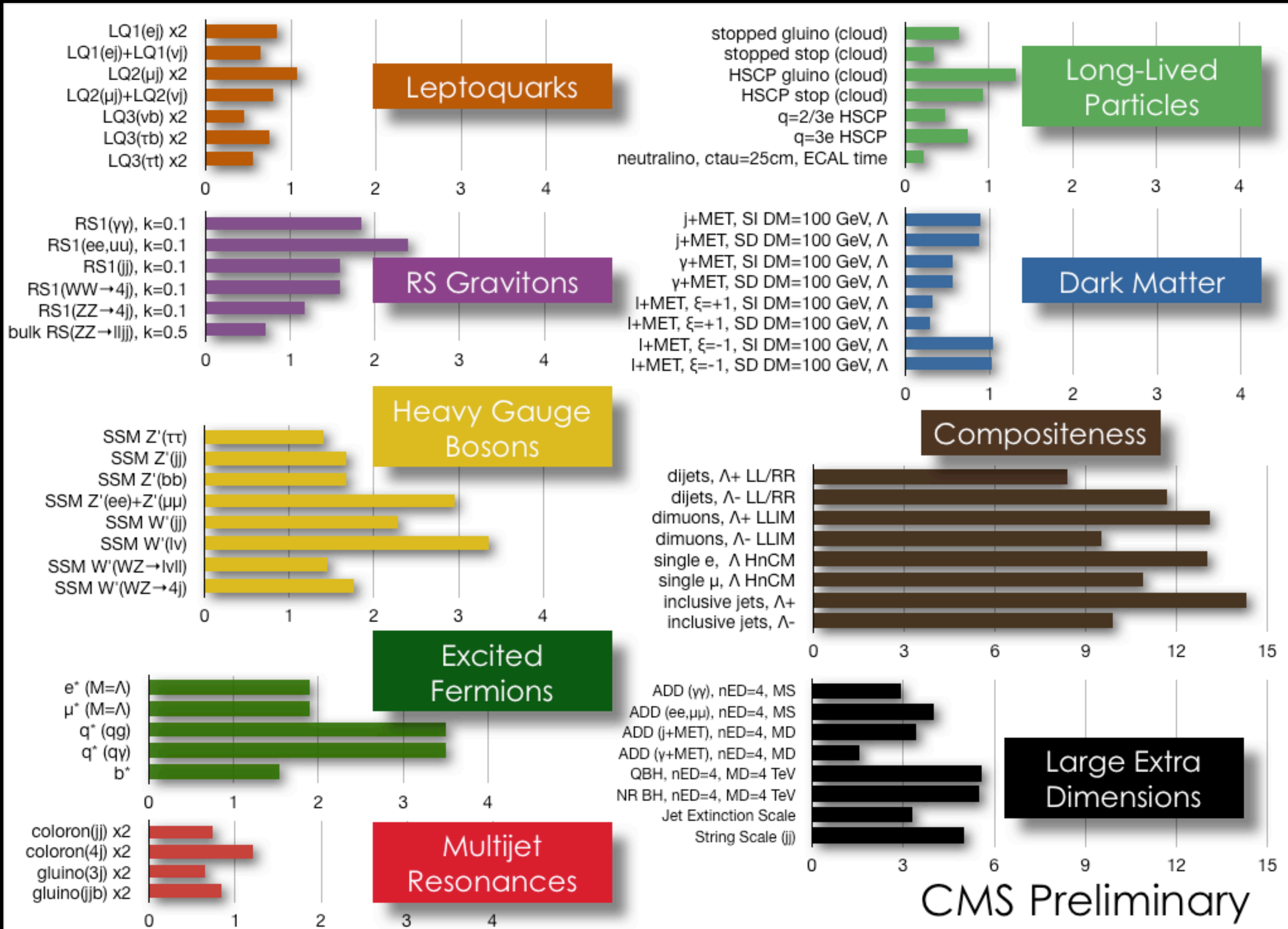
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

$\sqrt{s}$ = 7 TeV full data **$\sqrt{s}$ = 8 TeV partial data** **$\sqrt{s}$ = 8 TeV full data**

Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Overview of Other Searches



CMS Exotica Physics Group Summary – March, 2014

Summary of Run-1

- LHC machine and detector worked very well!
  - Machine ran at ~half the design energy
- >600 papers published in the past 4 years
  - Surprise #1: Found a new particle!!
    - The only fundamental scalar in Nature (so far)
    - Plays critical role in Standard Model
    - >2500 citations of observation paper per experiment
  - Surprise #2: No other new particles found!
    - No sign of Supersymmetry or any other new physics yet
    - Intense dialogue between theorists and experimentalists
      - >1000's of citations for SUSY search papers

LHC Roadmap

2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
….
2035

Run 1: $\sqrt{s}$=7-8 TeV, $\int L dt$=25 fb^{-1}, pileup $\mu \approx 20$

LS1: phase 0 upgrade

Run 2: $\sqrt{s} \approx 13$ TeV, $\int L dt \approx 120$ fb^{-1}, $\mu \approx 43$

LS2: phase 1 upgrade

Run 3: $\sqrt{s} \approx 14$ TeV, $\int L dt \approx 350$ fb^{-1}, μ=50-80

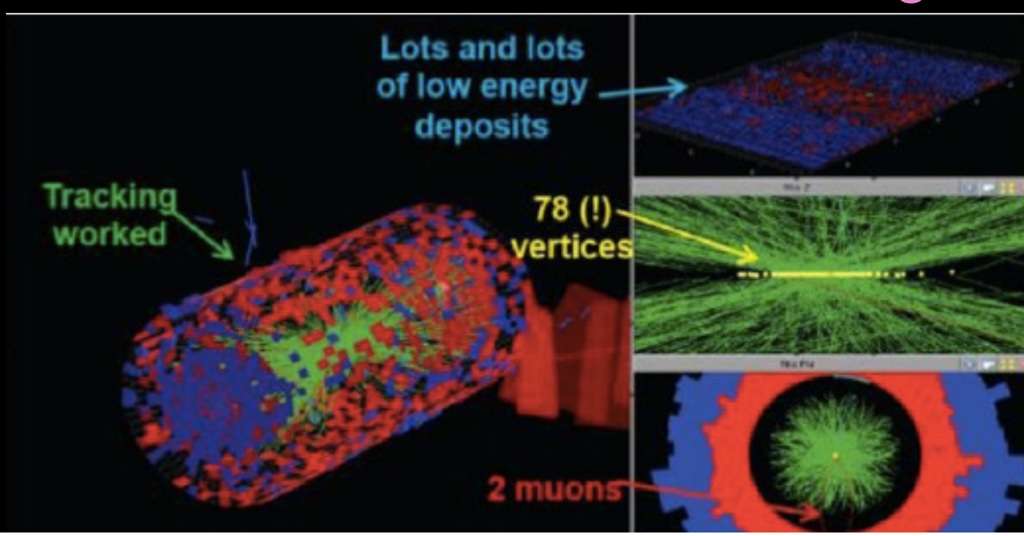
LS3: phase 2 upgrade

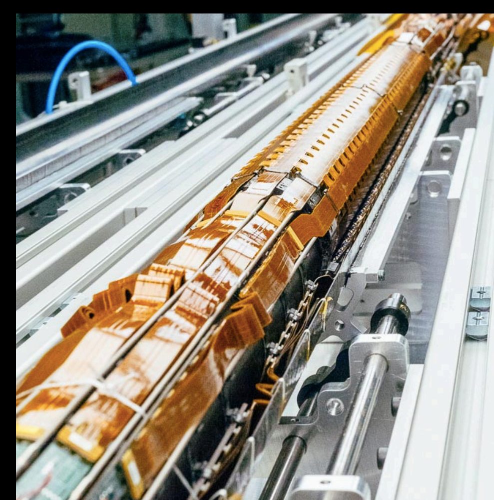
HL-LHC: $\sqrt{s} \approx 14$ TeV, $\int L dt \approx 3000$ fb^{-1}, $\mu \approx 140$-200

(updated by CERN: Dec. 2nd 2013)

Detector Upgrades

- Detectors will need to be upgraded to be able to cope with higher luminosity, e.g.
  - Improve trigger capabilities
    - better discriminate the desired signal events from background as early as possible in trigger decision
  - Upgrade and/or replace detectors as they e.g.
    - Cannot handle higher rate due to bandwidth limitations
    - Suffer from radiation damage making them less efficient





Detector Upgrades: Phase-0, Phase-I and Phase-II

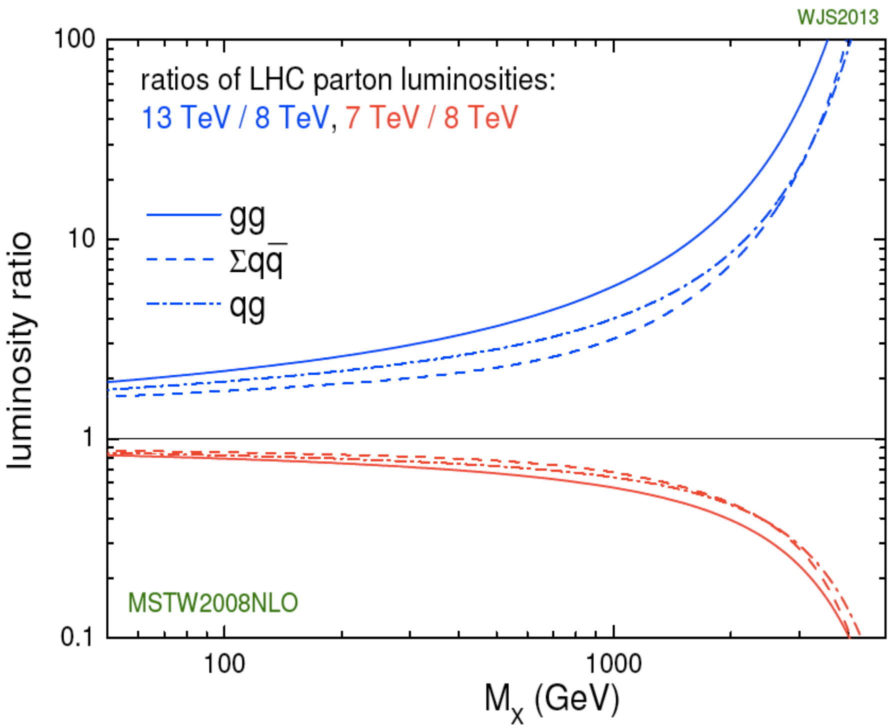
ATLAS

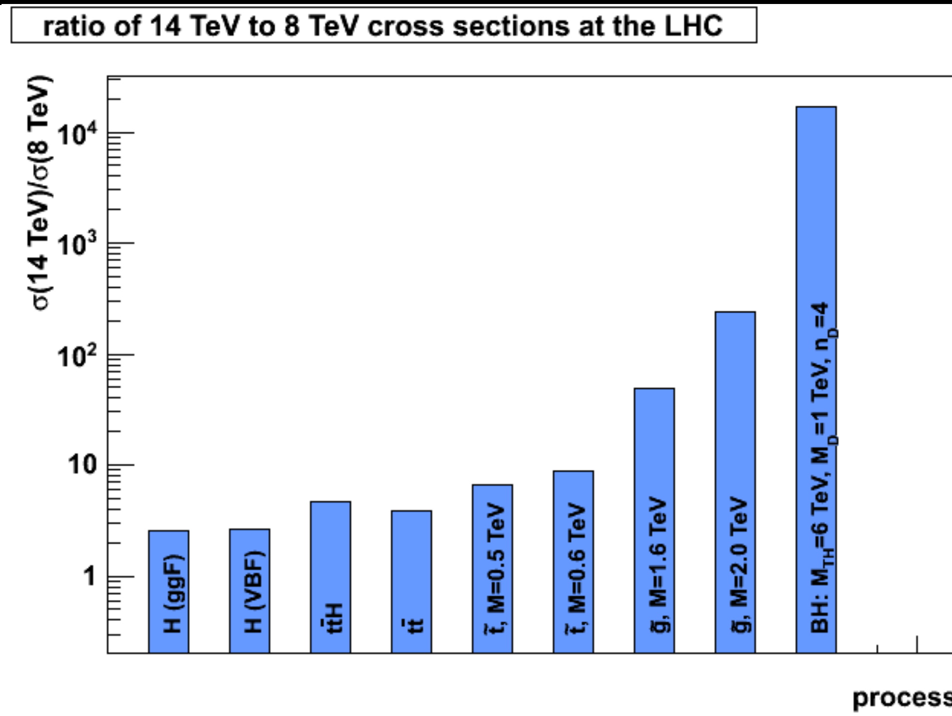
- Phase-0
  - 4th Si Pixel layer (IBL)
  - Complete muon coverage
  - Repairs (TRT, LAr and Tile)
  - New beampipe and infrastructure updates
- Phase-I
  - Fast Track Trigger (FTK)
  - Muon New Small Wheel (NSW)
  - LAr cal. electronics
- Phase-II
  - New pixel and strip tracker
  - Calorimeter
  - Muon system
  - Trigger system
  - Computing

CMS

- Phase-0
  - Complete muon coverage
  - Colder tracker
  - Photodetectors in HCAL
  - New beampipe and infrastructure updates
- Phase-I
  - New Si pixel tracker
  - L1 trigger upgrade
  - HCAL electronics
- Phase-II
  - New pixel and strip tracker
  - Calorimeter
  - Muon system
  - Trigger system
  - Computing

Run-2 Physics Cross Sections





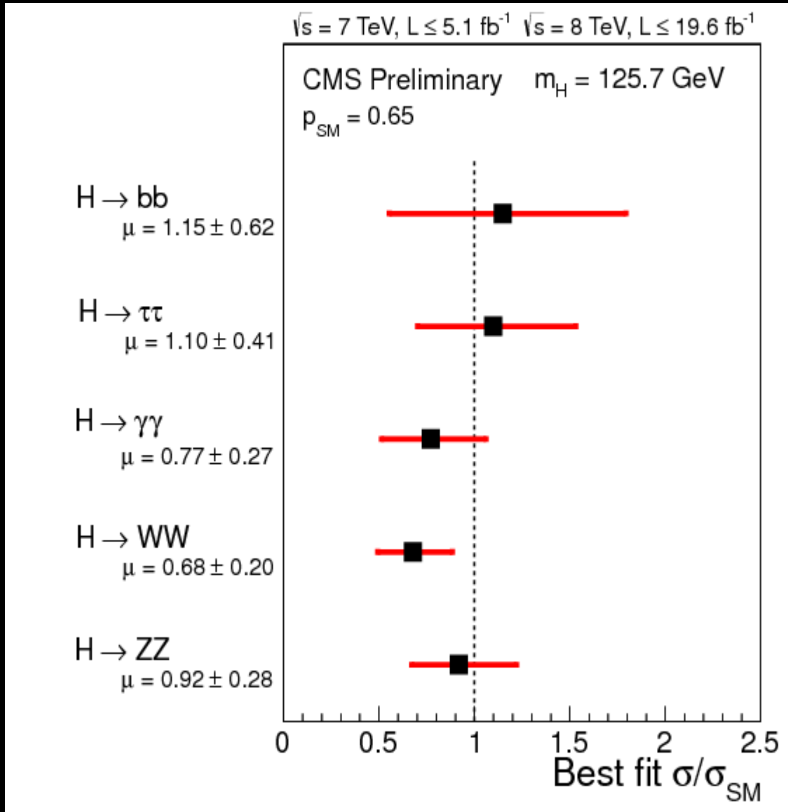
- Increase in cross section by factor ~10 for M~2 TeV
- With a few fb^{-1} discovery of TeV scale particles possible
  - Expect 15-30 fb^{-1} by end 2015

Higgs Boson Coupling Measurements

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Current Results on signal strength compared to SM



Observable number of Higgs events/exp

	Run-1	HL-LHC
H→4leptons	20	4,000
H→γγ	350	130,000
VBF H→ττ	50	20,000

Higgs studies have only just begun:

- Current precision on about 20-50%
- Need ~3% precision on couplings to probe TeV scale particles
- HL-LHC will increase Higgs dataset dramatically

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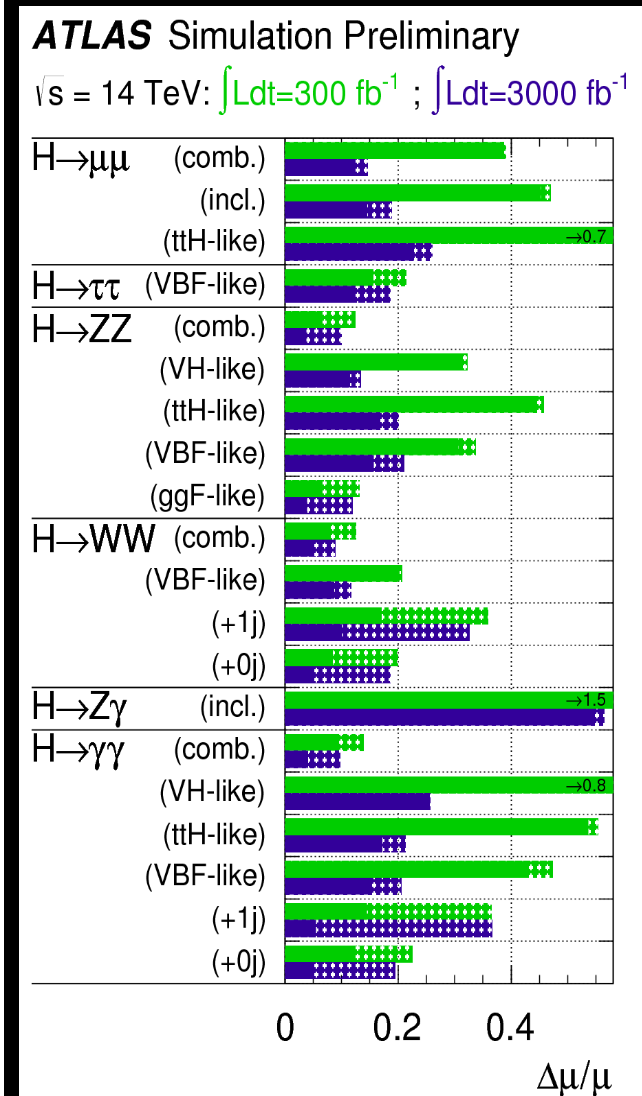
Future Higgs Boson Coupling Measurements

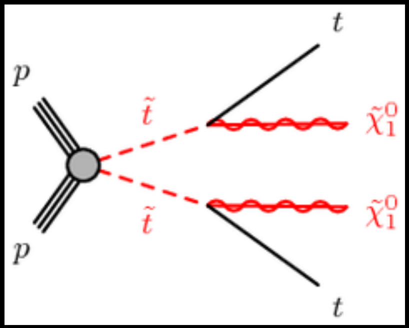


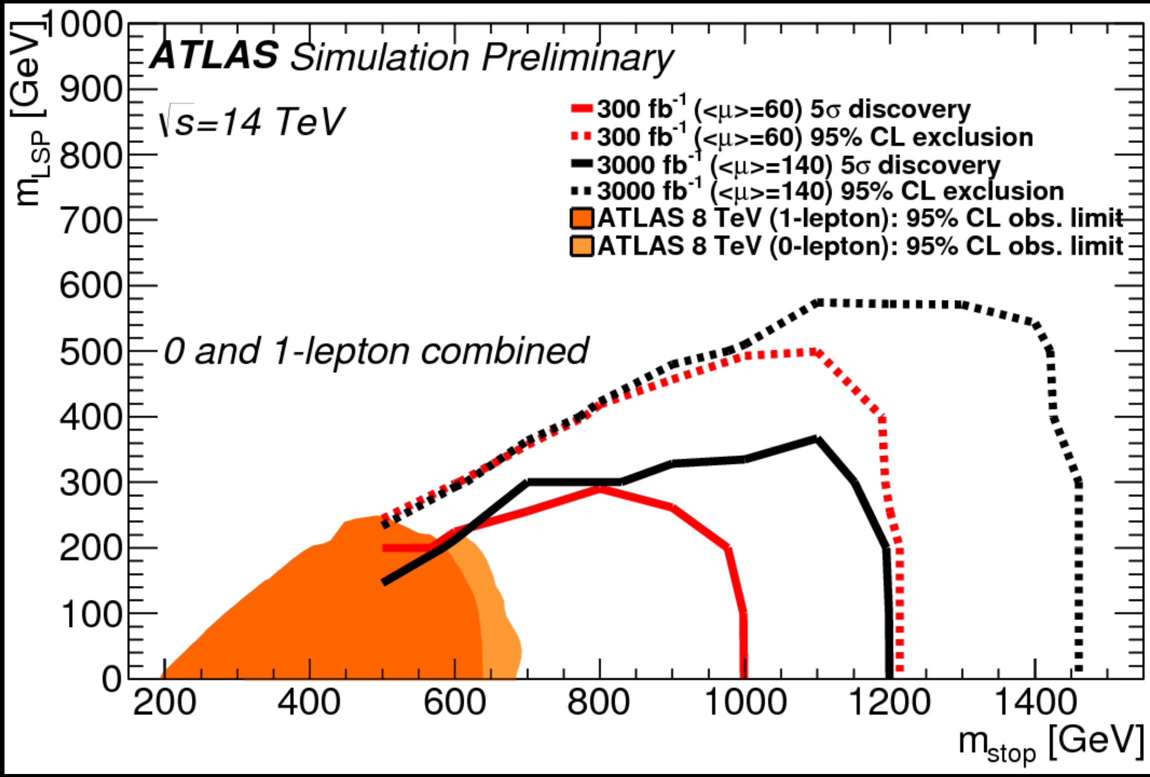
CMS projections for coupling precision (arXiv:1307.7135)

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

- Future LHC runs will enable precision Higgs physics
  - Couplings measured with 2-8% precision
  - Access to rare decays
    - E.g. how does it couple to muons?

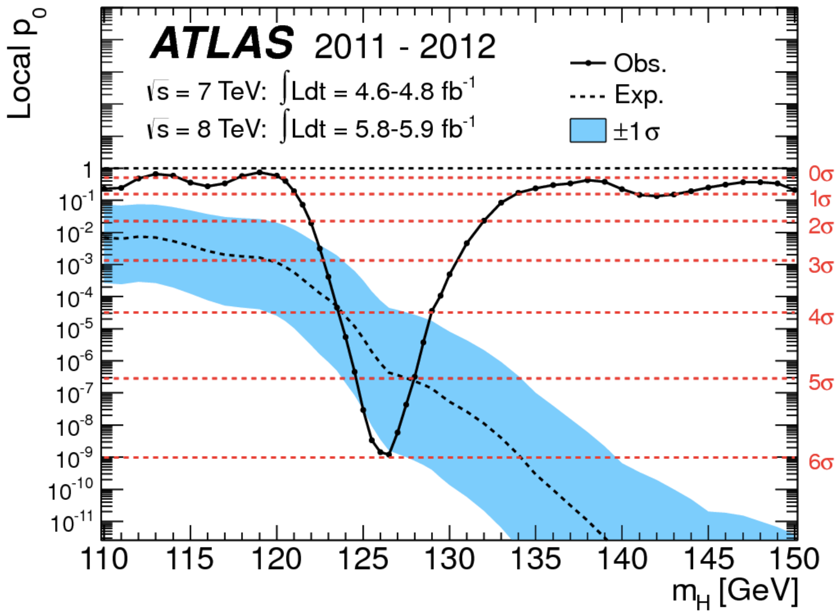
Future Prospects for SUSY Discovery





- Run-2 at LHC will approximately double mass reach compared to run-1
- Significant further increase with 3000 fb-1
- Will probe stop masses up to m=1.5 TeV
  - Gluinos up to m=2.5 TeV

Conclusions & Outlook I



- The LHC worked fantastically well
  - after >20 years of design and construction
- Found a new particle consistent with the Higgs boson
  - Program of property measurements is starting
    - With current precision fully consistent with SM Higgs boson
- No other new particles found yet

Conclusions & Outlook II

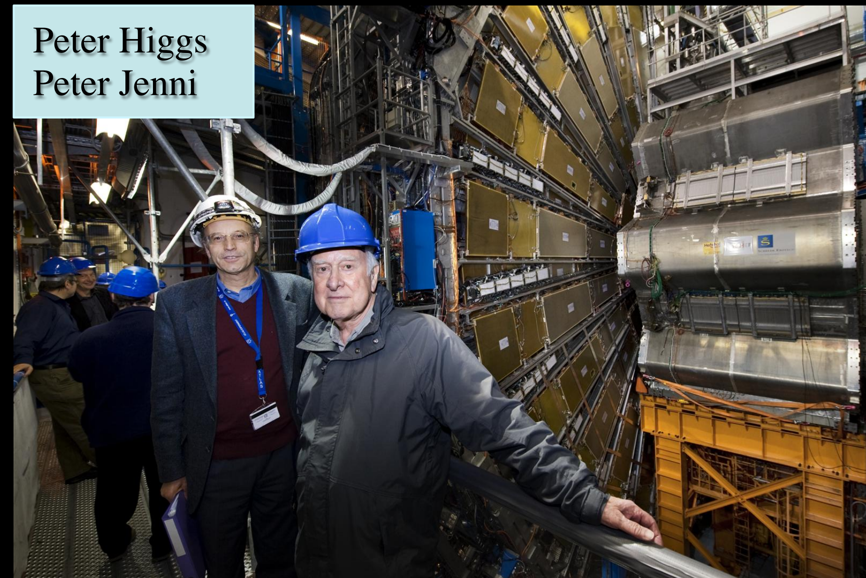
- This was just the beginning!!!
  - High energy running starting in 2015 ($\sqrt{s} \approx 13$ TeV)
    - Fully on schedule to start in Spring 2015
  - Increase luminosity by factor ~15 by 2021
    - … and another factor 10 by 2030
    - Major detector upgrade program under way
  - Will probe
    - Higgs couplings with 2-8% precision
    - Stop quarks up to ~1.5 TeV

More Information

- Information, explanations, movies, images …
  - http://public.web.cern.ch
  - http://atlas.ch
    http://cmsinfo.cern.ch/outreach

People at ATLAS

Berkeley Pixel Group 2007



Peter Higgs
Peter Jenni

Will I Am 2013
The Black Eyed Peas

Stephen Hawkings, 2013

Steve Chu, 2007